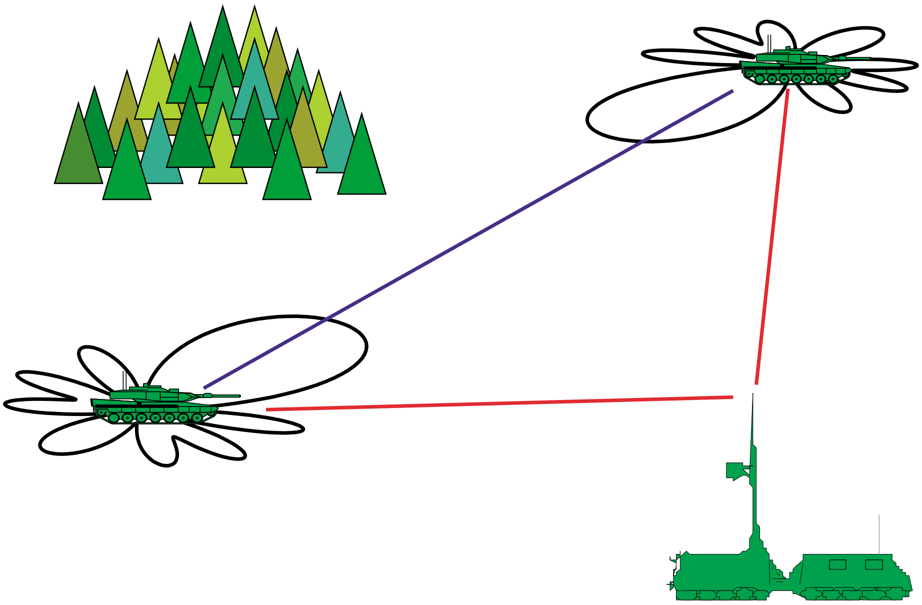
SWEDISH DEFENCE
RESEARCH AGENCY

FOI-R--0444--SE
March 2002
ISSN 1650-1942

Methodology Report

Karin Dyberg, Linda Farman

Antenna Arrays in Spatial reuse TDMA Ad Hoc Networks



Command and Control Systems
P.O. Box 1165
SE-581 11 LINKÖPING
SWEDEN

FOI- SWEDISH DEFENCE RESEARCH AGENCY
Command and Control Systems
P.O. Box 1165
SE-581 11 LINKÖPING
SWEDEN

FOI-R–0444–SE
March 2002
ISSN 1650-1942

Methodology Report

Karin Dyberg, Linda Farman

Antenna Arrays in Spatial reuse TDMA Ad Hoc Networks

Issuing organization

FOI- Swedish Defence Research Agency
Command and Control Systems
P.O. Box 1165
SE-581 11 LINKÖPING
SWEDEN

Report number, ISRN FOI-R–0444–SE	**Report type** Methodology Report
Reasearch area code 4. C4ISR	
Month year March 2002	**Project No.** E7759
Customers code 5. Commissioned Research	
Sub area code 41 C41	

Author/s

Karin Dyberg, Linda Farman

Project manager

Fredrik Eklöf

Approved by

Christian Jönsson

Sponsoring Agency

FMV- Defence Material Administration

Scientifically and technically responsible

Fredrik Eklöf

Report title

Antenna Arrays in Spatial reuse TDMA Ad Hoc Networks

Abstract

In modern military operations the requirements of transmitting large amounts of information have increased substantially during the last decade. This increases the demand for high-capacity radio networks. It is also essential that military decisions be made on recent and correct information, which requires that the delays are known and low. Other requirements are that the performance of the military radio network must be satisfactory in highly mobile scenarios and that the network must be robust against hostile jamming and other interfering sources.

We have investigated how the capacity and average delay can be improved in an Ad Hoc network with Spatial reuse Time Division Multiple Access (STDMA) by using antenna arrays. The study is based on different antenna combinations consisting of single isotropic antenna element, beam steering and adaptive beamforming. We have also studied how the number of antenna elements and the terrain affects the performance.

The study shows that the capacity is improved dramatically in the examined scenario, with up to 1200%. Also, the average delays are decreased when using antenna arrays instead of single isotropic antenna elements. The study also indicates that the benefit from antenna arrays is higher in a flat than in a rough terrain.

Keywords

Ad Hoc networks, Spatial TDMA, antenna arrays, beam steering, adaptive beamforming

Further bibliographic information	**Language English**
Also publicised by Linköping University, LITH-ITN-KTS-EX–01/07–SE	
ISSN 1650-1942	**Pages 89 p.**
	Price Acc. to pricelist

Utgivare
Totalförsvarets Forskningsinstitut-FOI
Avdelningen för Ledningssystem
Box 1165
581 11 LINKÖPING

Rapportnummer, ISRN
FOI-R–0444–SE

Klassificering
Methodology Report

Forskningsområde
4. Spaning och ledning

Månad, år
Mars 2002

Projektnummer
E7759

Verksamhetsgren
5. Uppdragsfinansierad verksamhet

Delområde
41 C41

Författare
Karin Dyberg, Linda Farman

Projektledare
Fredrik Eklöf

Godkänd av
Christian Jönsson

Uppdragsgivare/kundbeteckning
FMV- Försvarets materielverk

Teknisk och/eller vetenskapligt ansvarig
Fredrik Eklöf

Rapportens titel
Spatiell TDMA i Ad Hoc-nät med gruppantenner

Sammanfattning

Kravet på att överföra stora mängder information vid militära operationer har ökat avsevärt under det senaste årtiondet. I och med detta har efterfrågan på radionät med hög kapacitet ökat. Det är även viktigt att militära beslut grundas på aktuell och korrekt information, vilket kräver låga och kända fördröjningar.

Vi har undersökt hur kapaciteten och medelfördröjningen kan förbättras i ett Ad Hoc nät med Spatial Time Division Multiple Access (STDMA) genom att använda gruppantenner. Studien baseras på olika antennkombinationer bestående av rundstrålande antennelement, lobstyrning och adaptiv lobformning. Vi har också studerat hur antalet antennelement, terräng samt en ökad konnektivitet påverkar nätets prestanda.

Studien visar att kapaciteten kan förbättras med upp till 1200% och medelfördröjningen kan minskas genom att använda gruppantenner istället för ett ensamt rundstrålande antennelement. Vinsten i kapacitet och fördröjning varierar beroende på vilken lobformningskombination som används. Vinsten blir också olika stor beroende på hur gruppantennen används. Kapacitetsvinsten är högre när gruppantennen inte bara används för att undertrycka och minska interferenser utan också för att öka konnektiviteten.

Studien visar också att kapacitetsvinsten är högre när fler antennelement används för ett nät med ett stort antal länkar och att fördelarna med gruppantenner är högre i snäll terräng än i kuperad.

Nyckelord
Spatiell TDMA, Ad Hoc-nät, gruppantenner, lobstyrning, adaptiv lobformning

Övriga bibliografiska uppgifter
Språk Engelska
Har även publicerats av Linköpings universitet, LITH-ITN-KTS-EX–01/07–SE

ISSN 1650-1942
Antal sidor 89 s.

Distribution enligt missiv
Pris Enligt Prislista

Table of Contents

Nomenclature

BER	Bit-error-rate.
BPSK	Binary phase shift keying.
CSMA	Carrier Sense Multiple Access.
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance.
CTS	Clear to Send.
DOA	Direction of Arrival.
FDMA	Frequency Division Multiple Access.
LAN	Local Area Network.
LCMV	Linearly Constrained Minimum Variance.
MAC	Medium Access Control.
MSE	Mean-Square-Error.
RF	Radio Frequency.
RTS	Request to Send.
SINR	Signal-to-Interference-plus-Noise Ratio.
SNR	Signal-to-Noise Ratio.
STDMA	Spatial Time Division Multiple Access.
TDMA	Time Division Multiple Access.
UCA	Uniform Circular Array.
ULA	Uniform Linear Array.

$\mathbf{A}(\theta)$	L by M matrix, with its columns being the steering vectors of the antenna array.
$E[\ ]$	Statistical expectation.
K	Set of links.
L	Number of antenna elements.
Λ_a	Average relative traffic load in the network.

Λ_{ij}	Relative traffic load on link (i, j).
M	Number of links.
N	Number of nodes in a network.
P_{T}	Transmitted power.
R	Radius of the antenna array.
$\hat{\mathbf{R}}$	Sample covariance matrix.
$\mathbf{R}_{\mathrm{I+N}}$	True covariance matrix for interferers and noise.
T	Number of time slots in STDMA schedule.
$\mathbf{a}(\theta_m)$	Steering vector at the direction θ from signal m.
$a_l(\theta_m)$	Steering vector for antenna element l with respect to an emitted signal, m, at DOA θ.
$\alpha(t)$	Amplitude of the signal $\mathrm{s}(t)$.
β_l	Phase excitation of the lth antenna element.
$\mathbf{a}_{\mathrm{UCA}}(\theta)$	Steering vector for a UCA with the direction θ.
c	Speed of propagation of the plane wave front.
d	Distance between the antenna elements.
$d(n)$	Reference signal at time n.
$\varepsilon(n)$	Error between the array output and the reference signal at time n.
h_{ij}	Number of guaranteed time slots for link (i, j).
I_l	Amplitude excitation of the nth antenna element.
$\mathbf{k}$	Wave vector.
k	Wave number.
λ	The average of traffic arrival rate at node v_i with destination node v_j.
λ_{ij}	Average traffic load on link (i, j).
λ_{w}	Wavelength.
λ^*	Maximum throughput in the network.
μ	Total traffic out of the network.

μ_{ij}	Number of packets that can be transmitted per time slot by link (i, j).
$\mathbf{n}(n)$	Random noise.
$n_l(n)$	Random noise component on the *l*th antenna element.
ω	Carrier frequency.
$\omega(t)$	Center frequency of the signal $\mathrm{s}(t)$.
ϕ	Direction of the antenna gain or antenna factor in XY-plane.
$\phi(t)$	Phase of the signal $\mathrm{s}(t)$.
ϕ_0	Direction of the main beam.
ϕ_l	Angular position of the *n*th antenna element.
$\mathbf{r}_l$	Location vector of the *l*th element.
$\mathbf{r}_{\mathrm{xd}}$	Cross-covariance term between the received signal and reference signal.
σ_{d}^2	Variance of the reference signal.
σ_{n}^2	Variance of the noise.
$\mathbf{s}(t)$	A signal impinging on the array.
$s(n)$	Emitted signal at the antenna array at time *n*.
$s_m(n)$	Baseband signal for signal *m*.
θ	Azimuth angle.
τ	Propagation time across the array.
τ_{ij}	Number of time slots that have passed since the link was previously allocated one.
t_{ij}	Number of time slots allocated to link (i, j).
φ	Elevation angle.
$\mathbf{w}$	Array weight vector.
w_l	Weight at the *l*th antenna element.
$\mathbf{w}_{\mathrm{opt}}$	Optimal weights.
$\mathbf{x}(n)$	Array data vector at time *n*.
$x_l(n)$	Input at antenna element *l* due to an emitted signal at DOA θ.

$x_l(n)$	Received data at the *l*th antenna element.
$y(n)$	Array output at time *n*.
$*$	Complex conjugate.
$()^H$	Complex conjugate transpose of a vector or matrix.
$()^T$	Transpose of a vector or matrix.
(i, j)	A link between node v_i and node v_j

Chapter 1

Introduction

This chapter provides a background and introduction to the subject. It also includes motivations to this master thesis. The main objective of this study and the thesis outline are also presented in this chapter. If there is some uncertainty regarding the terminology used in radio communication, see Appendix A.

1.1 Background

Modern military operations are highly dependent on secure radio communications. The requirements of transmitting large amounts of information, for example situation awareness information[1], sensor information and order conveying, have increased substantially during the last decade. This increases the demand for high-capacity radio networks, i.e., a higher throughput of data. It is very important that military decisions be based on recent and correct information, which implies that low and known delays are required. Position distribution services are one example of when low delays are desirable. It is also essential that all users can be reached. This can be achieved by using multihop functionality. The increasing importance of joint operations[2] in the battlespace implies that different stations must be able to automatically and quickly connect into a common communications network. Other requirements are that the performance of the military radio network must be satisfactory in a highly mobile scenario and that

---

[1] For example position information.

[2] Operations involving army, navy and air force, both national and international.

the network must be robust against hostile jamming and other interfering sources.

The existing Swedish military radio communications do not meet the requirements for capacity, delay, highly mobile scenarios and robustness against hostile jammers that are anticipated in the future battlespace. A possible solution that has hitherto shown great promise and can meet these extremely challenging demands is the use of Spatial reuse Time Division Multiple Access (STDMA) in Ad Hoc networks with antenna arrays.

1.2 Problem overview

This section begins with a description of Ad Hoc networks, followed by a presentation of different Medium Access Control (MAC) protocols with the main focus on STDMA. The section also explains why STDMA is chosen for this study and why STDMA could be used with antenna arrays. Finally, the section presents previous work within this area.

1.2.1 Ad Hoc Network

Ad Hoc network, or Multihop Packet Radio Network, refers to a network of a set of radio stations, or nodes, which can all be mobile [30]. The network is totally wireless without any fixed infrastructure and can be dynamically and quickly created, i.e., the radio stations can be connected and disconnected without involving an administrative station. No centralised station exists in this type of network, which could be compared to a base station in a cellular network [1]. This means that every radio station must be able to either exchange packets directly or forward packets for other stations that cannot communicate directly with each other, i.e., each station can also function as a router. That is why the term “multihop” is used. The network provides peer-to-peer communications, which means that all radio stations can communicate directly with each other and no supervising station is needed. Today, Ad Hoc networks are most commonly used for military communications and also, to some extent, in civilian emergency situations [2], where the radio stations must be able to operate without the support of a fixed infrastructure. It is not only for military applications that Ad Hoc networks are interesting, but also for civilian uses. Today, considerable research is carried out to investigate whether Ad Hoc networks are applicable to, for example, LAN (Local Area Networks) ([27],[28]).

1.2.2 MAC protocols

The three primary design problems in multihop networks are the routing problem, the network-control problem, and the multi-access problem. The routing problem, due to the multihop functionality, deals with how a packet will find its way through the network to the final destination [29]. The network-control problem is a matter of how to preserve reliable operations as the network topology may change, i.e., the integrity of the network resources must be maintained and the network flows must be controlled. The multi-access problem concerns how to allocate a given radio spectrum to different users in such a way that the frequencies are efficiently utilised and the interferences between radio stations are minimised [31].

To solve the multi-access problem, several MAC protocols have been proposed. Two dynamic MAC protocols are ALOHA and Carrier Sense Multiple Access (CSMA). The ALOHA protocol transmits randomly without making sure whether the radio channel is idle, which might result in packet collision. Therefore randomised retransmission is required. In CSMA, the sender first senses for users on the radio channel and only transmits the packet if the channel is idle. If the channel is busy, the sender must for example wait a random time until it can sense the channel again. Despite this, senders might transmit simultaneously, and collisions occur. Collisions can also occur when a node cannot detect another transmitting node due to some kind of obstruction, for example a hill. This problem is known as the hidden-terminal problem. When collisions occur, the protocol handles the situation like ALOHA through a randomised retransmission. To alleviate the hidden-terminal problem some enhancements have been made to the CSMA protocol. This resulted in CSMA/CA (Collision Avoidance) [12]. CSMA/CA is based on “handshaking”. This means that the radio communications are initiated with a Request to Send (RTS) message, which in turn is answered with a Clear to Send (CTS) message. Finally, the data can be transmitted. In the RTS message, the sending node asks whether the channel is idle; if that is the case, the receiving node answers with a CTS message that tells other adjacent nodes that they are not allowed to send. The handshaking procedure minimises the risk of collisions, but the RTS messages can still collide. An advantage of the ALOHA and CSMA protocols is their simplicity, since no co-ordination between the radio stations is required. However, major disadvantages of these protocols include many unavoidable collisions at high traffic loads in the network and difficulties in providing a limit of the maximum delay.

To solve the problems with high traffic loads and delays, and to guarantee that packets reach their destination, static collision-free protocols can be used. Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) are two protocols that have this property. FDMA implies that users in the network are allocated different frequencies to send on, i.e., each channel is represented by a frequency. TDMA implies that each carrier frequency is divided into time slots, and every user is allocated a time slot. Both protocols utilise the radio spectrum relatively well when the radio stations are geographically close, but if the stations are geographically scattered, then the resources are poorly utilised. To achieve an efficient resource utilisation, Spatial reuse Time Division Multiple Access (STDMA), which is a variation of TDMA, has been proposed [13].

1.2.3 STDMA

STDMA is a MAC protocol, which utilises the radio spectrum more efficiently by allowing more than one radio station to use the same time slot if the interferences are sufficiently small. There are several STDMA algorithms proposed ([4],[11]). The purpose of STDMA algorithms is to allocate time slots to users on the basis of different criteria and to create a schedule, which contains information about which links that can be used in each time slot. The criteria used for the different algorithms are, for example, to generate a schedule that is as short as possible or to minimise delays in the network. Previous work shows that STDMA is suitable when the nodes are geographically scattered and the traffic loads are high. Compared to TDMA the STDMA protocol gives an improvement in terms of average delay and capacity [4]. Research has also been carried out on STDMA in mobile multihop networks [1].

Like most other MAC protocols, STDMA also has drawbacks. One drawback with STDMA is that when the nodes are geographically close together and thereby highly connected, the algorithm loses its main purpose and instead works like TDMA. The reason is that the interferences between the nodes become too high to let different nodes use the same time slot. Further drawbacks when using spatial reuse are that the schedules are sensitive to mobility [1], and that it is difficult to handle bursty data traffic. To make one improvement in the performance of Ad Hoc networks with STDMA, it has been proposed that STDMA could be used with antenna arrays [3].

1.2.4 Antenna arrays in radio communications networking

When receiving, antenna arrays can maximise the sensitivity in the direction of the desired signal and minimise the sensitivity in the direction of anticipated interferences and jammers. When transmitting, antenna arrays can direct the output power towards an anticipated receiver and minimise the output power in the directions of other nodes, thereby minimising the interferences to other users, see Figure 1. This implies that the Signal-to-Interference-plus-Noise Ratio (SINR) will be improved. SINR in this thesis is an energy ratio. In a military context, it is very useful to be able to direct the transmitted power and thus avoid transmitting in an anticipated direction of the enemy. Thereby the risk of being detected is decreased.

Between a transmitter and a receiver, the antenna arrays can be used to decrease the bit-error-rate (BER), increase the coverage, improve the accessibility, increase the capacity in terms of bit rate, improve robustness, and decrease the output power. For networks with STDMA, antenna arrays can be used to increase the capacity in terms of throughput, decrease the delays, increase the connectivity, and improve the performance in a highly mobile scenario and the robustness against interferences and jammers.

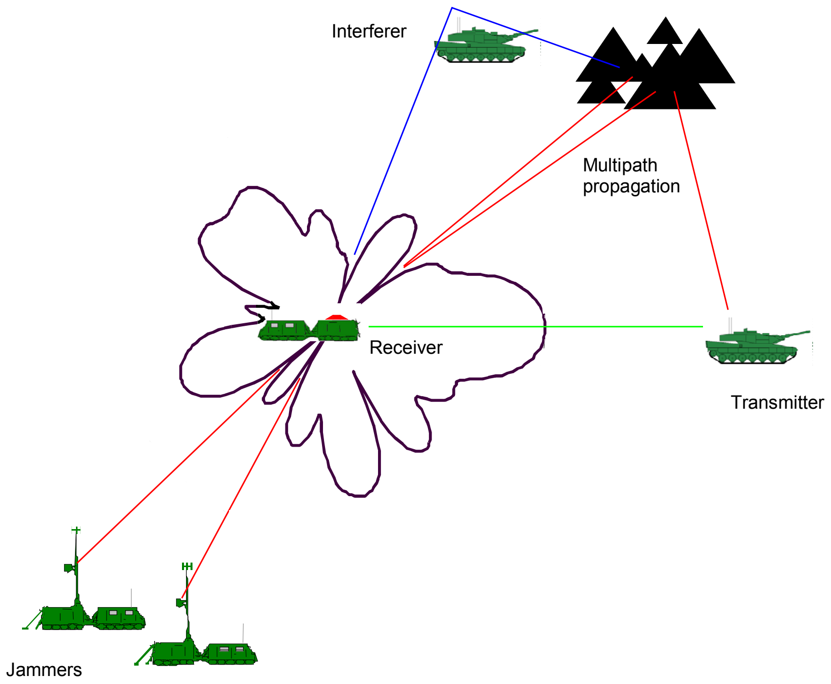


Figure 1. Illustration of how the effect of interferences, jammers and multipath propagation is minimised in a radio system with antenna arrays. By using antenna arrays, it is possible to adapt the radiation pattern, shown as the marked area around the receiver, for the antenna system. In this way, the sensitivity in the directions to intentional jammers and interferences is minimised, while it is maximised in the direction of the desired signal.

1.2.5 Previous work

Extensive research has been carried out on antenna arrays on the network level, but mainly for centralised networks such as the second and third generation mobile telephone systems ([16], [17]). Therefore, studies of antenna arrays in Ad Hoc networks are of great interest. One example of research in this area is CSMA/CA with a switched beam antenna array [9]. The study, investigating different types of switched beam strategies, shows a substantial throughput improvement and a reduced average packet delay. The advantages of beam steering in an Ad Hoc network with STDMA have been examined in [3]. The model used was a four-element antenna and a simple maximum-gain array processing scheme. The two sample networks in the study, each consisting of ten nodes, were simulated in two different terrains, rough and flat. The simulation results show that the capacity in the multihop network can be improved by 50-70 percent compared to a system with only single isotropic antenna elements.

Another related work is the research carried out on slotted ALOHA with adaptive beamforming [22]. For the slotted ALOHA, the carrier frequency is divided into time slots to decrease the risk of packet collisions. The idea of using adaptive antennas is to allow a node to receive several packets successfully in each time slot, also known as space division multiple access (SDMA). The conclusion from this research is that throughput is increased by use of adaptive beamforming.

A study on CSMA/CA considering both beam steering and switched beams is presented in [21]. However, the beamforming antennas are only used for transmitting, and a single isotropic antenna element is used for receiving. In this study two types of CSMA/CA were considered: Aggressive Collision Avoidance and Conservative Collision Avoidance. The first method only considers whether the intended node is transmitting or receiving. The receiving status of other nodes is disregarded, which means that collisions may occur. The second method avoids this problem by only permitting transmission if none of the other nodes in its range is busy. Throughout the study, a stationary network of 40 nodes is considered. Parameters studied to see the performance of the system are network density[3], gain and number of beams for the switched beamforming. The performance is measured in throughput and average delay. The research shows an improvement in throughput and a reduction in end-to-end average delay. One conclusion of the research is that link power control is essential if the benefits of beamforming antennas should be exploited to their fullest. Another conclusion is that switched beams are nearly as good as beam steering when spatial reuse is considered.

As discussed above, STDMA in Ad Hoc networks has many advantages but also weak points. However, it seems that these weak points might be compensated by the advantages of antenna arrays. The improvements achieved by antenna arrays, as shown in the limited research that has been done in this area, motivate further investigations such as implementing more advanced beamforming methods.

1.3 Objective

The main objective is to investigate how the capacity and average delay can be improved by using antenna arrays in an Ad Hoc network with STDMA. No previous study has been performed on the chosen STDMA algorithm with antenna arrays. A study of the antenna combinations with single isotropic antenna elements for transmitting and adaptive beamforming for receiving, as well as beam steering for transmitting and adaptive beamforming for receiving is also an additional contribution within this area.

1.4 Thesis outline

We define the problem in Chapter 2, which includes a description of different parameters that are of interest for this study, the delimitations and assumptions made, and finally the different models used. Chapter 3 describes the solution method used and how it is validated. In Chapter 4 we describe the MAC protocol STDMA and the algorithm used. The fundamentals of antenna arrays, different beamforming strategies for

---

[3] The number of nodes per area station.

antenna arrays and the antenna array signal processing are presented in Chapter 5. This chapter also concerns different ways of using antenna arrays and different beamforming algorithms, although the focus lies on the chosen algorithms. Chapter 6 begins with a description of the performance measurements including capacity and average delay, and concludes with a presentation of the simulations carried out. In Chapter 7 the results from the simulations are given. The conclusions drawn from the simulation results are presented in Chapter 8. Finally, in Chapter 9 suggestions for future work within this area are described. In Appendix A, common terminology concerning radio communication is described. Appendix B gives the average results from the simulations.

Chapter 2

Problem definition and model assumptions

This chapter gives a more detailed description of the problem. It includes the parameters we have chosen in order to see how they affect the performance measurements. The chapter also gives the delimitations and descriptions of the models used.

2.1 Description

The STDMA algorithm used for this study provides a collision-free network and a relatively efficient resource utilisation [9]. One difference compared to other STDMA algorithms is that this one takes traffic loads into consideration. The study is based on STDMA in Ad Hoc networks combined with four different antenna combinations. These combinations are:

1. Single isotropic antenna element for transmitting and receiving.
2. Single isotropic antenna element for transmitting and adaptive beamforming for receiving.
3. Beam steering for transmitting and adaptive beamforming for receiving.
4. Beam steering for transmitting and receiving.

The adaptive beamforming algorithm used in this study is the reference-signal-based beamforming; the beam steering algorithm used is the conventional beamforming. These algorithms are further described in Chapter 5.

The main reason for considering the case with a single isotropic antenna element is that the transmission uses broadcast. Also, at low frequencies, only a few antenna elements can be used because of the limited size of the typical platforms. Therefore, the theoretical antenna array gain is small. The antenna coupling and the vehicle platform affect the beam pattern, thus reducing the practically achievable antenna gain. Despite few antenna elements, severe antenna coupling and platform effects it is still possible for some algorithms to perform adaptive beamforming when receiving, e.g. with reference-signal-based beamforming. With an increased number of antenna elements it becomes possible to use beam steering when transmitting. The beam steering algorithm is less complex and generally requires less calculation capacity compared with adaptive beamforming. In a mobile scenario, beam steering is therefore more appropriate in scenarios where it can be difficult to update the beam pattern as often as necessary when using adaptive beamforming. The algorithm, in some situations, is also more robust compared with an adaptive algorithm, since the beam steering algorithm is only based on the direction of the desired signal. Therefore, in situations when adaptive beamforming might not work properly, for example due to smart jammers, the less complex beam steering algorithm can be more appropriate. Thus, in some situations beam steering is preferable when transmitting and receiving.

To show the improvements, the different beamforming combinations are compared with the single isotropic antenna element combination.

In a stationary network, capacity and average delay are analysed for the beamforming combinations. The performance measurements, capacity and average delay, are further described in Chapter 6.

2.1.1 Parameters

In this study the following parameters are chosen to see how they affect the capacity and average delay:

- Terrain (two types of terrain: rough and flat).
- Number of antenna elements.

- Increased connectivity in the network, i.e. increased number of links due to the use of antenna arrays.

2.2 Models and assumptions

To be able to study the problem, some delimitations and assumptions have been made. The delimitations as well as the descriptions of the models used concerning channel, topology, traffic, STDMA algorithm and beamforming algorithms are described below.

2.2.1 Delimitations

To limit the size of the problem the following delimitations have been made:

- The networks consist of 20 nodes.
- A node is able to send and receive packets, but not simultaneously.
- A node is only able to send/receive packets to/from one node at a time.
- The networks are connected, i.e. all nodes can reach all other nodes through multihop when studying capacity and average delay.
- All nodes are assumed to know the positions of all other nodes as well as everything about the channel to them.
- $SNR \geq 10$ dB is required for a link to be established.
- $SINR \geq 10$ dB is required for a link to be used.
- No comparison between different MAC protocols is made; only one STDMA algorithm will be used.
- The frequency is 300 MHz.
- The bit rate is 256 000 bits/second.
- Narrowband beamforming is considered.
- Only one adaptive beamforming algorithm will be used.
- All antenna elements will be isotropic.
- Only circular antenna arrays will be studied.
- No multipath arrivals will be considered.
- The elevation angle is assumed to be zero.

2.2.2 Model description

1. Channel model

In the radio network a channel is equivalent to a link. For a link to be established, the SNR value must exceed a certain threshold. The threshold is set to 10 dB because the modulation scheme binary phase shift keying (BPSK), which is often used, requires this threshold to guarantee a sufficiently good BER. Furthermore, the SINR for each link determines which nodes can communicate simultaneously. The model used in this study does not consider multipath propagation, i.e. it is assumed that the propagation is terrain dependent only. Although this is not very realistic in real-world scenarios, it has to be done because the simulation program that we use already has this limitation.

2. Topology model

Two different types of terrains are used, Lomben and Skara, which are representative of rough and flat terrains. The nodes are randomly distributed and scattered over a certain region in the terrain. When the locations of the nodes are known, the channel model is used to determine possible links. The locations of the nodes in the terrain will determine which pairs of nodes that can establish a link or not, since the distance and the terrain between the nodes affect the elementary path loss. To determine this elementary path loss we use the program Detvag-90.

3. Detvag-90

Detvag-90 is a wave propagation model operating in the frequency range 10 kHz-10 GHz. The model is mainly used for wave propagation calculations along the surface of the earth for moderate antenna heights and does not consider effects of the ionosphere and the troposphere. Detvag-90 is able to estimate the elementary path loss from one point to another and along given paths. It can also perform area coverage calculations around given transmission sites.

The terrain along the path is provided by a terrain database. Detvag-90 uses map databases from Lantmäteriet (National Land Survey) and Satellitbild AB (Swedish Space Corporation, SSC). These databases cover the entire area of Sweden and contain information about the topology and vegetation. A more detailed description of Detvag-90 can be found in [20].

4. Traffic model

We assume that packets of equal size arrive at the network according to a Poisson process. Only one packet can be sent in each time slot, and the buffer queue will grow to infinity if a node carries a heavier traffic load than it can handle. We also assume unicast communications and a uniform traffic model, i.e. all nodes have the same probability to be an arrival or a destination point of a packet.

The routing protocol used in this study is shortest path routing, since this protocol is already implemented in the simulation program we use, see Chapter 3.

5. STDMA algorithm

To achieve a collision-free network we use the STDMA algorithm described in [9]. This algorithm, like some others ([4], [11]), takes traffic loads into consideration. This means that if a link has a traffic load more than average, then the link is guaranteed additional time slots. By taking the traffic loads into consideration for each link, traffic congestion is prevented. To further improve the protocol, links are ordered in a priority list. The priority is based on traffic loads and the number of time slots that have passed since the link was previously allocated one. In an attempt to spread out the time slots assigned to each link, the priority is taken into consideration when generating the STDMA schedule. This will result in a decreased average delay [4]. For STDMA, synchronisation is assumed.

6. Beamforming algorithms

The two different types of beamforming methods implemented for antenna arrays are beam steering and adaptive beamforming. The method of using a single isotropic antenna element is also implemented as a reference.

The adaptive beamforming algorithm used in this study is the reference-signal-based beamforming algorithm. The basic idea with this algorithm is to minimise the MSE between the total received signal and the reference signal [7]. As a reference signal, a known training signal is used, i.e. a sequence of data that is known to the receiver. One reason for using this algorithm is that the direction of the desired signal does not have to be known. Another reason is that the algorithm provides a well-adapted radiation pattern when perfect synchronising is achieved, an assumption which is already made for STDMA. We also assume that the interferences that occur when the training signal is transmitted are the same as when the information is transmitted.

The beam steering algorithm used in this study is the conventional beamforming, which is a non-adaptive beamforming. The array pattern is maximised for a specified direction by letting the weights have equal magnitudes and only change the phase of the received data in each antenna element to steer the antenna array in a particular direction [7]. This algorithm is based on a good knowledge of the direction of the desired signal. We assume that the direction of the desired receiver/transmitter is known with sufficient precision, which enables us to steer the beam in the right direction.

7. Power level

The power level for all beamforming combinations is the power required for a network with single isotropic antenna element to be connected, i.e. if the power is slightly decreased, one node in the network will be disconnected.

Chapter 3

Solution method

This chapter describes the solution method used to solve the problem, where the chosen method is to carry out simulations. The chapter also discusses how the simulations are validated.

3.1 Simulation

To be able to study different beamforming combinations and the chosen parameters for STDMA in Ad Hoc networks, several simulations have to be carried out. To do this, an already existing simulation program is used, in which our program is included. The simulation program, written in C++, is responsible for creating the routing protocol. From a given schedule, created by a chosen MAC protocol, the simulation program then transmits packets in the network.

Our program, also written in C++, consists partly of the chosen STDMA algorithm, and partly of the four different antenna combinations. The antenna combinations that are implemented are:

1. Combination 1 - Single isotropic antenna element for transmitting and receiving.
2. Combination 2 - Single isotropic antenna element for transmitting and adaptive beamforming for receiving.
3. Combination 3 - Beam steering for transmitting and adaptive beamforming for receiving.
4. Combination 4 - Beam steering for transmitting and receiving.

Each of the antenna combinations functions as a parameter in the STDMA algorithm, and can thus be varied during the simulations. To perform the adaptive beamforming the reference-signal-based beamforming algorithm is implemented; for the beam steering, the conventional beamforming algorithm is implemented. A general picture of the relation between the existing program and our program is given in Figure 2.

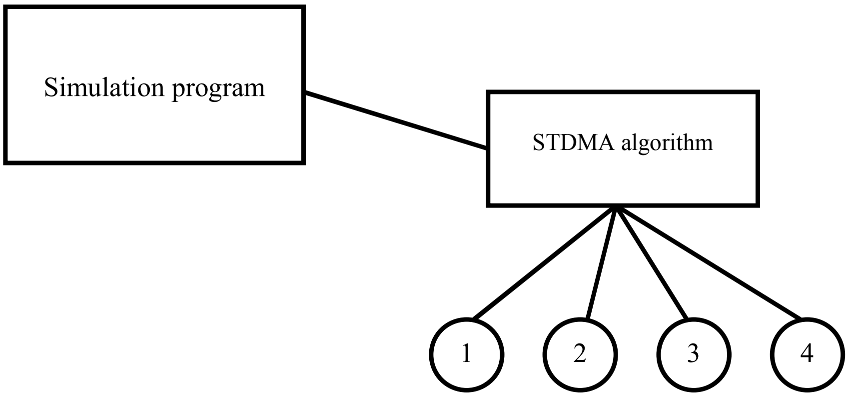


Figure 2. The relation between the existing program and our program.

3.2 Validation

The simulations carried out in our study are hard to validate. There are different means of validating simulation results. One approach is to compare the simulation results to results from a real-world implementation of a network. This is not possible in our study, since there is no real-world system to compare with. Therefore in our case, it is difficult to validate the output from the simulations. Instead we have tried to validate the different algorithms separately.

To validate our implementation of the STDMA algorithm we compared the STDMA schedule for a small network created by our program to a manually created STDMA schedule.

The implementation of the reference-signal-based beamforming algorithm is validated by a comparison between the output of our algorithm and the output of another implementation in Matlab. To validate our implementation of the conventional beamforming algorithm, we have plotted the results and come to the conclusion that the implementation is numerically correct.

The results from our simulations are also compared to results from other research work within this area to see whether the results are plausible.

Chapter 4

STDMA

The purpose of this chapter is to give a detailed description of the chosen STDMA algorithm.

4.1 The STDMA algorithm

There are two main reasons why we have chosen STDMA as the MAC protocol. Firstly, this protocol enables us to increase the resource utilization of the radio spectrum compared to, for example, TDMA or FDMA, which means an increased capacity in the network. In other words, when using STDMA the radio stations in the network can use the same time slot simultaneously if the interferences are sufficiently small. Secondly, the STDMA algorithm decreases the average delay in the network, compared to, for example, TDMA, since the number of time slots allocated to a link is based on the traffic load on the link. To decrease the average delay the STDMA algorithm distributes the time slots evenly over the schedule.

Assume that packets of equal size arrive at the network according to a Poisson process with mean λ, which is measured in packets per time slot. λ is called the traffic arrival rate. The average of traffic arrival rate at node v_i with destination node v_j is defined as

$$\frac{\lambda}{N(N-1)} \tag{4.1}$$

where N is the total number of nodes. Since some nodes forward packets for other nodes, which cannot communicate directly with each other, the traffic load on each link is not uniform. Before the traffic load on each link can be calculated, the traffic has to be routed, i.e. the path of the traffic has to be determined. Depending on the structure of the network the links will have different traffic loads. The average traffic load on link (i, j) is

$$\lambda_{ij} = \frac{\lambda}{N(N-1)} \cdot \Lambda_{ij} \tag{4.2}$$

where Λ_{ij} is the relative traffic load on link (i, j). The relative traffic load is a traffic load measurement, which is independent of the traffic arriving at the network. The relative traffic Λ_{ij} is defined in [10] as

$$\Lambda_{ij} = \frac{\lambda_{ij}}{\frac{\lambda}{N(N-1)}}. \tag{4.3}$$

Let h_{ij} be the guaranteed number of time slots allocated to link (i, j). Thus we have

$$h_{ij} = \left\lceil \frac{\Lambda_{ij}}{\Lambda_a} \right\rceil, \tag{4.4}$$

where Λ_a is the average relative traffic load in the network, i.e.

$$\Lambda_a = \frac{1}{M} \sum_{(i,j) \in K} \Lambda_{ij} \tag{4.5}$$

where M is the number of links and K is the set of links. Links with a high relative traffic load will be allocated several time slots, and to decrease traffic delays the time slots for each link have to be spread out over the STDMA schedule. To do so, time slots are allocated by priority based on the relative traffic load and τ_{ij}, which is the number of time slots that have passed since the link was previously allocated one. The link priority is set to

$$\tau_{ij} \cdot \Lambda_{ij} . \tag{4.6}$$

There are two conditions that must be fulfilled for a set of links, k, to be used in the same time slot, where k is a subset of K. Firstly, the SINR must exceed a certain threshold γ_1:

$$SINR_{ij} \geq \gamma_1 \qquad \forall (i, j) \in k , \tag{4.7}$$

where $k \subseteq K$.

Secondly, a node can either transmit or receive one packet in a time slot.

If $(i, j) \in k$, then no other link containing i or j can be in *k*. (4.8)

If conditions (4.7) and (4.8) are fulfilled for a set of $k \in K$, then the links in k can be used simultaneously [5].

The set of links that are allocated time slot t is called k_t. The links that have not been allocated their guaranteed time slots are listed in list A, and the links that have been allocated all their time slots are listed in list B.

The algorithm

```
Step 1 Initialise:
Calculate how many time slots each link is guaranteed according to equation (4.4).
1.1 Set $\tau_{ij}$ to zero for all links.
1.2 Create two lists, A and B, where A contains all the links and B is empty.

Step 2 Repeat until list A is empty:
2.1 Set $t \leftarrow t+1$ and $k_t \leftarrow 0$.
2.2 For each link $(i,j)$ in list A:
    i.   Set $k_t \leftarrow k_t \cup (i,j)$.
    ii.  If the links in $k_t$ can be used simultaneously,
         • Set $\tau_{ij}$ to zero.
         • Move $(i,j)$ to list B if the link has been allocated all its guaranteed time slots.
    iii. If the links in $k_t$ can not be used simultaneously,
         • Set $k_t \leftarrow k_t \setminus (i,j)$.
         • Set $\tau_{ij} \leftarrow \tau_{ij}+1$.
2.3 For each link $(i,j)$ in list B but not in $k_t$:
    i.   Set $k_t \leftarrow k_t \cup (i,j)$.
    ii.  If the links in $k_t$ can be used simultaneously,
         • Set $\tau_{ij}$ to zero.
    iii. If the links in $k_t$ can not be used simultaneously,
         • Set $k_t \leftarrow k_t \setminus (i,j)$.
         • Set $\tau_{ij} \leftarrow \tau_{ij}+1$.
2.4 Reorder lists A and B according to link priority $\tau_{ij} \cdot \Lambda_{ij}$, with highest priority first.
```

Chapter 5

Antenna arrays

This chapter describes the fundamentals of antenna arrays and beamforming. It also gives a description of signal processing of antenna arrays and different ways of using them. Finally, the two beamforming algorithms used in this study, reference-signal-based beamforming and conventional beamforming, are described ([7],[14],[24]).

5.1 Fundamentals of antenna arrays

This section describes of the antenna array and its radiation pattern.

5.1.1 What is an antenna array?

An antenna array consists of a number of antenna elements, which make it possible to radiate or receive electromagnetic waves more effectively in some directions than in others. The power distribution of an antenna array can be shown by a radiation pattern. The antenna array can take different geometries. Two common antenna arrays are the uniform linear array (ULA) and the uniform circular array (UCA), see Figure 3.

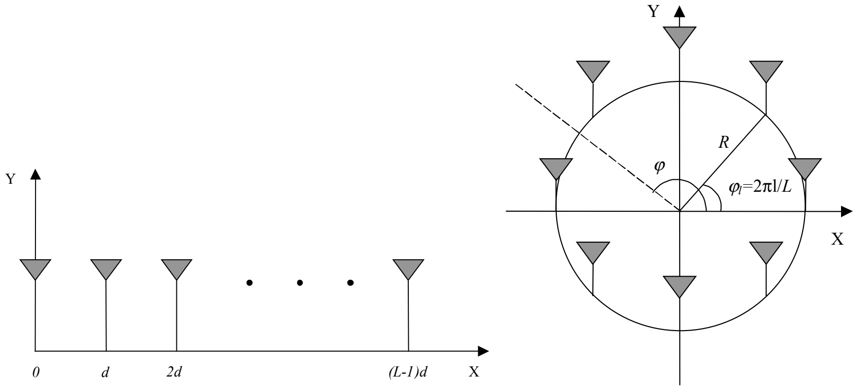


Figure 3. Examples of common antenna array geometries. A ULA (left) and A UCA (right), with L antenna elements. The azimuth angle of the received wave is defined as φ.

5.1.2 Radiation pattern

The radiation pattern is, as defined in [14], “a graphical representation of the radiation properties of the antenna as a function of space coordinates”. As mentioned above, the antenna array has the ability to adapt the radiation pattern to the current scenario. Each antenna element in the antenna array has its own fixed radiation pattern. In this study each antenna element is assumed to be an isotropic radiator, i.e. each antenna element has equal radiation in all directions.

When transmitting, the radiation pattern of the antenna represents the power distribution for all directions. When receiving, the radiation pattern represents the sensitivity in different directions.

The radiation pattern contains a number of lobes, which have different shapes and sizes, see Figure 4. The lobes can be divided into major, side and back lobes. The major lobe, also called the main beam, represents the direction of maximum radiation, i.e. the direction where the output power is highest. Any lobe beside the main beam is a side lobe and has a direction other than the main beam. Finally, the lobe with a direction that is opposite the main beam is called the back lobe. A trade-off has to be made between the main beam and the side lobes; for example by allowing a wider main beam the side lobes can be reduced. It is often desirable to minimize the side lobes, since they usually represent radiation in undesired directions. The level of the side lobes is usually expressed as a ratio of the power density in the lobe in question to the major lobe. Between the lobes the output power is very low, and these directions are defined as the null directions.

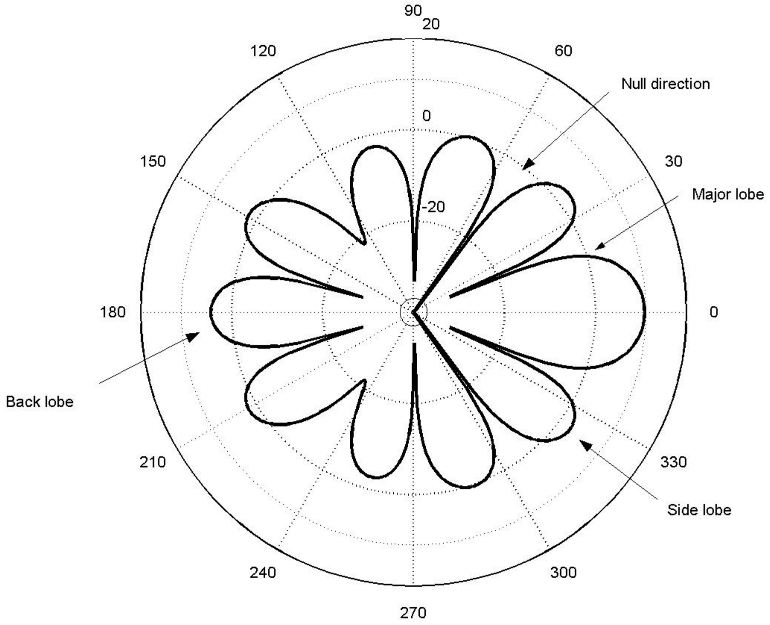


Figure 4. Two-dimensional radiation pattern of a circular antenna array with eight antenna elements, where the main beam is steered towards $\varphi = 0$, given in dB.

It is preferable to place the antenna elements a half wavelength of the radio signal apart from each other to avoid ambiguities. The size of the antenna array therefore depends on the frequency used, since the frequency is proportionally related to the wavelength. The radiation pattern of the antenna array is affected by the number of antenna elements used. Generally, more antenna elements give a better ability to suppress interferers, thanks to the increased number of null directions. In theory the number of antenna elements minus one interferences can be suppressed. In addition, the more antenna elements that are used, the narrower the shape of the major lobe becomes, giving a higher antenna gain. Antenna arrays, therefore, function better at high frequencies because this implies that more antenna elements can be used, without increasing the dimension of the antenna array.

5.2 Beamforming for antenna arrays

In this study we consider narrowband digital beamforming, which is described below.

5.2.1 Narrowband digital beamforming

In narrowband digital beamforming, the received signals in each antenna element are separately digitalised and converted into baseband signals. The beamforming is then performed by multiplying the received data in each antenna element by separate complex weights, whereupon they are added. In this way the phase and amplitude of the signal in each antenna element are modified, and the desired signal components can be added constructively. In a similar way, signals from other directions than the desired one are added destructively. The radiation pattern is formed when the weighted signals from each antenna element are summed up, see Figure 5.

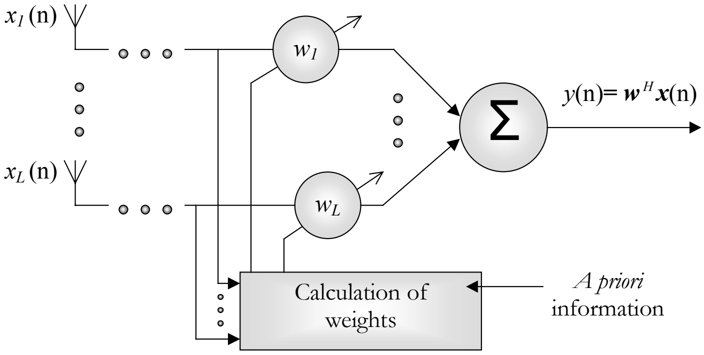


Figure 5. General structure of a narrowband beamformer.

In simple terms, it is assumed that all incident fields can be decomposed into a discrete number of plane waves; in other words, there is a finite number of signals. A beamformer used for narrowband signals samples the propagation wave field in space. At time n the output of the beamformer, $y(n)$, is given by a linear combination of the data at the L antenna elements [7], as shown in the following equation

$$y(n) = \sum_{l=1}^{L} w_l^* x_l(n) = \mathbf{w}^H \mathbf{x}(n). \tag{5.1}$$

In the equation the following notations are used:

* complex conjugate;
w_l the weight of the *l*th antenna element;
$x_l(n)$ the data at the *l*th antenna element;
$\mathbf{x}(n)$ array data vector at time n;
$\mathbf{w}^H$ weight vector, where the superscript H represents Hermitian (complex conjugate) transpose.

The weight vector is

$$\mathbf{w} = \left[w_1 \cdots w_L \right]^T . \tag{5.2 }$$

Data in the antenna elements are multiplied by weights to manipulate the phase and the amplitude of the signal. The sum of all data gives the output of the beamformer, which could be represented as a multi-input single-output system.

It is also possible to perform beamforming on broadband signals. The beamforming can then be performed either with a Tapped Delay Line (TDL) beamformer in the time domain [23] or frequency-based beamforming ([7], [8]).

5.3 Beamforming strategies

There are three different strategies for using antenna arrays: switched beams, beam steering, and adaptive beamforming.

5.3.1 Switched beam

For a switched beam system, several radiation patterns for different directions of the main beam are calculated in advance and saved. It is preferable that the differences between these directions are as small as possible. This gives a large amount of overlapping radiation patterns to choose among, see Figure 6. The radiation pattern that is chosen is the one having the major lobe closest to the direction of the desired signal. The choice of radiation pattern can be based on known information in terms of DOA or the correlation between a reference signal and the transmitted signal. Depending on the directions from which the interferences arrive and the level of the side lobes, the suppression is of different grades.

There are advantages and disadvantages to switched beam systems. The advantages are that the system has the ability to suppress interferences, and is less complex and less expensive compared to adaptive beamforming systems. One disadvantage is that the system cannot the radiation pattern according to the signal environment since all the radiation patterns are calculated in advance, see Figure 7 (i). Other disadvantages are that the system is unable to provide any protection from multipath components, which arrive with DOAs near that of the desired component, and generally the system is not able to take advantage of multipath propagation.

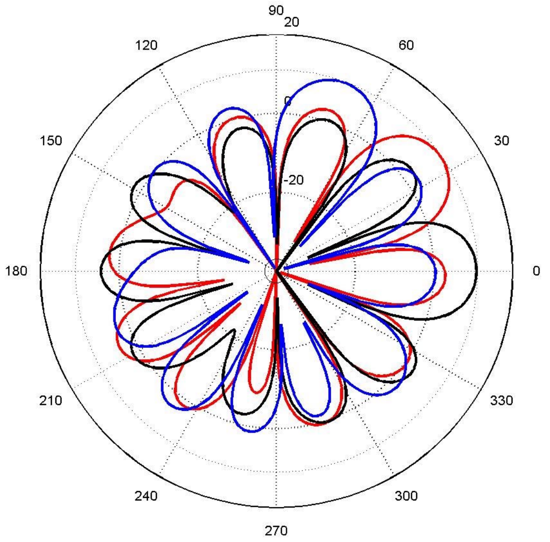


Figure 6. A switched beam system with radiation patterns calculated in advance. In a switched beam system the radiation pattern that has the major lobe closest to the desired signal is chosen.

5.3.2 Beam steering

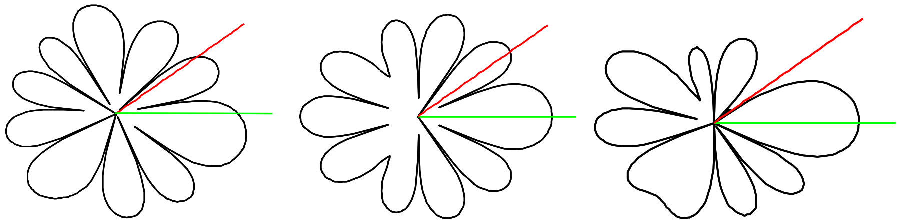
Unlike a switched beam system, where the radiation pattern is calculated in advance, a beam steering system calculates the radiation pattern each time the direction of the desired signal changes. Beam steering gives the ability to follow the desired signal and maximise the power radiated in this direction. However, the system cannot adapt the radiation pattern to suppress interferences when receiving, or to avoid sending in certain directions, see Figure 7 (ii). This makes the system sensitive when receiving, since an interfering signal might not be sufficiently suppressed if the signal impinges on a side lobe.

One advantage of beam steering systems, like switched beam systems, is that the systems are less complex and generally require less calculation capacity compared to adaptive beamforming systems. The beam steering system is also less sensitive to a smart jammer. A disadvantage, as mentioned above, is that the systems are unable to steer the null directions.

5.3.3 Adaptive beamforming

Adaptive beamforming gives the ability to adjust the radiation pattern according to changes in the signal environment. To adjust the radiation pattern, the gain and phase of the received signal in each antenna element are modified. In receiving, the adaptive beamforming maximises the sensitivity in the direction of the desired signal and minimises the sensitivity in the direction of interfering sources, see Figure 7 (iii). Correlated multipath components of the desired signal can either be used, i.e. added constructively, or suppressed.

However, the adaptive beamforming also has difficulties. Adaptive beamforming systems are complex and require high calculation capacity. They also require information that might not always be available, for example the direction of a certain signal and how the channel affects the signal. Furthermore, in a highly mobile situation it may be hard to adjust the radiation pattern as often as required. The reason for this may be that the capacity that is available for calculation of the radiation pattern is not high enough, which implies that the time for calculation will increase.



(i) (ii) (iii)

Figure 7. The difference between switched beam, beam steering and adaptive beamforming. A switched beam system is not able to adjust the radiation pattern and direct the main beam since all the radiation patterns are calculated in advance, see (i). In (ii) a beam steering system with the major lobe in a desired direction is shown. The beam steering system cannot adapt the radiation pattern to suppress interferences when receiving or to avoid sending in certain directions. The adaptive beamforming system is shown in (iii). The major lobe is steered in the direction of the desired signal, and the null directions are placed in the directions of interferers.

5.4 Narrowband signal model

Assume that an antenna array of arbitrary geometry with L antenna elements receives the waveforms generated by a number of point sources. Each antenna element gives an output, impulse response, which can be modelled as the response of a linear time-invariant system. The physical antenna structure, the receiver electronics in the antenna element, and the signal parameters will affect the response. The other antenna elements in the array will also affect the response because of mutual coupling.

A signal $s(t)$ impinging on the array can be expressed as

$$s(t) = \alpha(t)\cos(\omega t + \phi(t)) \tag{5.3}$$

where

t continuous time;

$\alpha(t)$	the amplitude of the signal;
$\omega = 2\pi f$	in which f is the carrier frequency;
$\phi(t)$	the phase of the signal.

The signal is defined as narrowband if the amplitude and phase of the signal vary slowly with respect to the propagation time, τ, across the array, i.e. if

$$\alpha(t-\tau) \approx \alpha(t) \text{ and } \phi(t-\tau) \approx \phi(t)\,. \tag{5.4}$$

This assumption implies that the narrowband signal can be written as

$$\begin{aligned} & s(t-\tau) = \alpha(t-\tau)\cos(\omega(t-\tau)+\phi(t-\tau)) \approx \\ & \alpha(t)\cos(\omega t - \omega\tau + \phi(t)) \end{aligned} \tag{5.5}$$

and thereby the time delay of the signal can be modelled as a simple phase shift of the carrier frequency. The time delay is due to the same signal reaching each antenna element at different times because of the differences in the propagation paths.

For a narrowband signal reaching the *l*th antenna element, the time delay of propagation can be modelled as a simple phase shift. In complex notation, this is represented by multiplying a signal by

$$e^{-i\mathbf{r}_l^T\mathbf{k}(\varphi)}, \tag{5.6}$$

which represents the propagation effect of a signal to a location $\mathbf{r}_l$. The location vector $\mathbf{r}_l$ and the wave-vector $\mathbf{k}$ are described later in this section.

Assume that each antenna element for an antenna array is represented as a point in a coordinate system in the XYZ plane, with the origin as the time reference. In the 3D case the position of the *l*th element with respect to some reference point, here the origin, is given by the location vector defined as follows

$$\mathbf{r}_l = R\left[\cos(2\pi(l-1)/L), \quad \sin(2\pi(l-1)/L), \quad \tan\theta\right]^T, \tag{5.7}$$

where

θ the elevation angle;

$R = \dfrac{d}{2\sin(\pi/L)}$

and d is the distance between the antenna elements. In this study d is chosen to be $\lambda_\text{w}/2$, where λ_w is the wavelength.

The so-called wave vector is defined as $\mathbf{k}(\varphi,\theta)$ and its magnitude $|\mathbf{k}| = k = \omega/c$ is the wave number. The wave number can also be written as $k = 2\pi/\lambda_\text{w}$. In [24] the XYZ plane the wave vector is defined as

$$\mathbf{k}(\varphi,\theta) = -\frac{\omega}{c}\begin{bmatrix}\cos\varphi\cos\theta \\ \sin\varphi\cos\theta \\ \sin\theta\end{bmatrix} = -\frac{2\pi}{\lambda_\text{w}}\begin{bmatrix}\cos\varphi\cos\theta \\ \sin\varphi\cos\theta \\ \sin\theta\end{bmatrix}, \tag{5.8}$$

where

c the speed of propagation of the plane wave front;
$\omega = 2\pi f$ where f is the carrier frequency.

In this study the elevation angle is not taken into consideration, thus $\theta = 0$. This implies that

$$\mathbf{r}_l = R\left[\cos(2\pi(l-1)/L), \quad \sin(2\pi(l-1)/L)\right]^T \tag{5.9}$$

and

$$\mathbf{k}(\varphi) = -\frac{\omega}{c}\begin{bmatrix}\cos\varphi \\ \sin\varphi\end{bmatrix} = -\frac{2\pi}{\lambda_{\mathrm{w}}}\begin{bmatrix}\cos\varphi \\ \sin\varphi\end{bmatrix}. \tag{5.10}$$

The steering vector, or array response, models the response of the array to an emitter signal at the direction of arrival φ. Each antenna element has an antenna gain, which in this study is equal to one. In the 2D case, the steering vector takes the form

$$\mathbf{a}(\varphi) = \left[e^{-i\mathbf{r}_1^T\mathbf{k}(\varphi)}, \ldots, e^{-i\mathbf{r}_L^T\mathbf{k}(\varphi)}\right]^T, \tag{5.11}$$

which is valid for a circular antenna array with isotropic antenna elements. Equations (5.9) and (5.10) in (5.11) give

$$\mathbf{a}(\varphi) = \left[e^{i\frac{\pi}{2\sin(\pi/L)}\cos(\varphi)} \; e^{i\frac{\pi}{2\sin(\pi/L)}\cos(\varphi - 2\pi/L)}, \ldots, e^{i\frac{\pi}{2\sin(\pi/L)}\cos(\varphi - 2\pi(L-1)/L)}\right]^T. \tag{5.12}$$

The received data at antenna element l at the discrete time n with respect to an emitted signal, m, at DOA φ is defined as

$$x_l(n) = a_l(\varphi_m)s_m(n). \tag{5.13}$$

If M signals from distinct DOAs reach an antenna array with L antenna elements, the input vector is defined as

$$\mathbf{x}(n) = \sum_{m=1}^{M}\mathbf{a}(\varphi_m)s_m(n) \tag{5.14}$$

where $s_m(n)$ denotes the *m*th baseband signal. By defining a steering matrix

$$\mathbf{A}(\varphi)=\begin{bmatrix} a_l(\varphi_1) & \cdots & a_l(\varphi_M) \\ \vdots & & \vdots \\ a_L(\varphi_1) & \cdots & a_L(\varphi_M) \end{bmatrix} \tag{5.15}$$

and a vector of signals

$$\mathbf{s}(n)=\left[s_1(n),\ldots,s_M(n)\right]^T, \tag{5.16}$$

the equation for the received data can be put in a more compact form

$$\mathbf{x}(n)=\begin{bmatrix} x_1(n) \\ \vdots \\ x_L(n) \end{bmatrix}=\sum_{m=1}^{M}\begin{bmatrix} a_1(\varphi_m) \\ \vdots \\ a_L(\varphi_m) \end{bmatrix}s_m(n)+\begin{bmatrix} n_1(n) \\ \vdots \\ n_L(n) \end{bmatrix}=\mathbf{A}(\boldsymbol{\varphi})\mathbf{s}(n)+\mathbf{n}(n). \tag{5.17}$$

To obtain a correct model, the noise $\mathbf{n}(n)$ must be added. The noise term is independent of $\mathbf{s}(n)$. In equation (5.17), $\mathbf{n}(n)$ is a random noise component on the *l*th element, which includes background noise and electronic noise generated in the *l*th channel. The noise is assumed to be white Gaussian noise with zero mean and variance equal to one.

5.5 Beamforming algorithms

There are several adaptive beamforming algorithms, which can be divided into three classes based on what type of *a priori* information they need. These classes are

- Algorithms that use information about the DOA [26].

- Algorithms that use known characteristic of the signal [16] [17].
- Algorithms that use an explicit reference signal [18] [19].

The beam steering algorithm used for this study is conventional beamforming and the adaptive beamforming algorithm used is reference-signal-based beamforming. These algorithms are described below.

5.5.1 Conventional beamforming

The conventional beamforming algorithm is chosen in this study mainly because of its simplicity. It has relatively high side lobes, but a narrow main lobe, which is preferable.

The basic idea with this algorithm is to maximise the antenna gain in the desired direction φ. The maximising of the output power is formulated in [24] as

$$\begin{aligned}&\max_{\mathbf{w}} E\left\{\mathbf{w}^H\mathbf{x}(n)\mathbf{x}^H(n)\mathbf{w}\right\} = \max_{\mathbf{w}} \mathbf{w}^H E\left\{\mathbf{x}(n)\mathbf{x}^H(n)\right\}\mathbf{w} = \\ &\max_{\mathbf{w}}\left\{E\left|s(n)\right|^2\left|\mathbf{w}^H\mathbf{a}(\varphi)\right|^2 + \sigma^2\left|\mathbf{w}\right|^2\right\}.\end{aligned} \tag{5.18}$$

The norm of $\mathbf{w}$ is constrained to $\left|\mathbf{w}\right| = 1$ when carrying out the above maximisation. The resulting solution is then

$$\mathbf{w}_{\mathrm{BF}} = \frac{\mathbf{a}(\varphi)}{\sqrt{\mathbf{a}^H(\varphi)\mathbf{a}(\varphi)}}\,, \tag{5.19}$$

which is the weight vector of the conventional beamforming. See equation (5.12) for definition of the steering vector $\mathbf{a}(\varphi)$.

5.5.2 Reference-signal-based beamforming

Reference-signal-based beamforming is chosen for this study because first of all the direction of the desired signal does not need to be known, which is an advantage since this information can be difficult to get. The algorithm works well even though a small number of antenna elements are used.

The basic idea with the reference-signal-based beamforming is to minimise the error between the beamformer output and the known reference signal ([17], [18], [19]). To adjust the weights, a known training signal is transmitted. At the receiver the training signal is used to calculate the weights in order to make the beamformer output as equal as possible to the reference signal. Unfortunately, the training signal requires resources in the network, which could instead be used to transmit the data. A weakness of this algorithm can be if additional interferences appear when the real information is sent/received, since no consideration has been given to these when calculating the beamforming weights.

The reference-signal-based beamforming algorithm requires synchronisation. If the network is not synchronised, synchronisation is achieved with the training signal before the beamforming. Problems may occur if the signals from interferers are correlated with the training signal, which increases the probability of synchronisation errors. The error between the reference signal and the array output can be calculated as in [19]

$$\varepsilon(n) = d(n) - y(n) = d(n) - \mathbf{w}^H \mathbf{x}(n) \tag{5.20}$$

where

$\varepsilon(n)$	error at time *n*;
$d(n)$	reference signal at time *n*;
$\mathbf{x}(n)$	array data vector a time *n*;
$\mathbf{w}^H$	weight vector;

$y(n)$ array output.

The weights are chosen to minimise the mean-square error (MSE) between the beamformer output and the reference signal. The squared error is defined as

$$\varepsilon^2(n) = \left[d(n) - \mathbf{w}^H \mathbf{x}(n) \right]^2 . \tag{5.21}$$

The statistical expectation of the squared error can be written as

$$\begin{aligned} &E\left[\ |\varepsilon|^2 \right] = \\ &E\left[d^2(n) - d(n)\mathbf{x}(n)^H \mathbf{w} - d^*(n)\mathbf{w}^H \mathbf{x}(n) + \mathbf{w}^H \mathbf{x}(n)\mathbf{x}(n)^H \mathbf{w} \right]. \end{aligned} \tag{5.22}$$

Since the statistical expectation of a sum is the sum of all the statistical expectations, the expression above can be written as

$$E\left[|\varepsilon|^2 \right] = E\left[d^2(n) \right] - E\left[d(n)\mathbf{x}(n)^H \right]\mathbf{w} - \mathbf{w}^H E\left[d*(n)\mathbf{x}(n) \right] + \mathbf{w}^H E\left[\mathbf{x}(n)\mathbf{x}(n)^H \right]\mathbf{w} . \tag{5.23}$$

The weight vector is independent of the time and can therefore be put outside the brackets of the statistical expectation. The statistical expectations above can be stated by considering the variance of the reference signal

$$E\left[d^2(n) \right] = \sigma_{\mathrm{d}}^2 \tag{5.24}$$

the cross-covariance terms between the reference signal and the received signal

$$E\left[d(n)\mathbf{x}(n)^H\right]=\mathbf{r}_{\mathrm{xd}}^H \text{ and } E\left[d^*(n)\mathbf{x}(n)\right]=\mathbf{r}_{\mathrm{xd}} \tag{5.25}$$

and finally the theoretical covariance matrix, $\mathbf{R}$

$$E\left[\mathbf{x}(n)\mathbf{x}(n)^H\right]=\mathbf{R}\,. \tag{5.26}$$

The mean square error can then be written as

$$E\left[|\varepsilon|^2\right]=\sigma_{\mathrm{d}}^2-\mathbf{r}_{\mathrm{xd}}^H\mathbf{w}-\mathbf{w}^H\mathbf{r}_{\mathrm{xd}}+\mathbf{w}^H\mathbf{R}\mathbf{w}\ . \tag{5.27}$$

The minimum is given by setting the gradient vector of (5.27) with respect to $\mathbf{w}$ equal to zero

$$\nabla_{\mathrm{w}}E\left[|\varepsilon|^2\right]=2(-\mathbf{r}_{\mathrm{xd}}+\mathbf{R}\mathbf{w}_{\mathrm{opt}})=0\,. \tag{5.28}$$

Finally, (5.28) gives the optimal weights in the MSE sense

$$\mathbf{w}_{\mathrm{opt}}=\mathbf{R}^{-1}\mathbf{r}_{\mathrm{xd}}\,. \tag{5.29}$$

It is not possible to determine the true covariance matrix in practice, since an infinite number of samples would be necessary. Therefore the sample covariance matrix, $\hat{\mathbf{R}}$, which is an estimation over a finite number of samples, is used to represent the true covariance matrix.

5.5.3 Calculation of the SINR

The weights are used to calculate the SINR [25]

$$SINR = \frac{P_{\mathrm{T}} \left| \mathbf{w}^{H} \mathbf{a}_{1}(\varphi) \right|^{2}}{\mathbf{w}^{H} \mathbf{R}_{\mathrm{I+N}} \mathbf{w}} \tag{5.30}$$

where

P_{T}	the transmitted power;
$\mathbf{w}^{H}$	the weight vector;
$\mathbf{a}_{1}(\varphi)$	the steering vector for the desired signal;
$\mathbf{R}_{\mathrm{I+N}}$	the sample covariance matrix for interferers and noise.

Chapter 6

Evaluation

The first part of this chapter describes of the performance measurements used in this study, and the second part presents the different simulations that are carried out.

6.1 Performance measurements

This section describes the performance measurements capacity and average delay.

6.1.1 Capacity

Capacity is measured in terms of maximal throughput. The maximum throughput, λ^*, is defined as the largest input traffic arrival rate for which the expected average delay is finite [15]. The capacity gain is calculated as the ratio between the maximum throughput for a beamforming combination, and the maximum throughput for the combination with isotropic antenna element for transmitting and receiving.

The maximum throughput is the greatest traffic arrival rate, which can arrive at the network without making the network unstable. The network becomes unstable when the traffic arrival rate, λ, is higher than the network can handle. This means that one or several nodes are not able to transmit the packets fast enough, which implies that the queues will increase and eventually the delays in the network will reach infinity.

The number of packets per time slot that can be transmitted by link (i, j) is

$$\mu_{ij} = \frac{t_{ij}}{T} \tag{6.1}$$

where

T number of time slots in the STDMA schedule;
t_{ij} number of time slots is allocated to link (i, j).

As stated in (4.2), the traffic load on link (i, j) is

$$\lambda_{ij} = \frac{\lambda}{N(N-1)} \cdot \Lambda_{ij}$$

where

N number of nodes;
Λ_{ij} the relative traffic load on link (i, j).

The network is stable if $\lambda_{ij} \le \mu_{ij}$ for all links (i, j). This implies that

$$\frac{\lambda}{N(N-1)} \cdot \Lambda_{ij} \le \frac{t_{ij}}{T} \tag{6.2}$$

for all links (i, j). The maximum throughput is reached when equality in equation (6.2) holds for at least one link. The maximum throughput can therefore be written as

$$\lambda^* = \min_{(i,j)} \left\{ \frac{N(N-1)}{T} \cdot \frac{t_{ij}}{\Lambda_{ij}} \right\} \tag{6.3}$$

6.1.2 Delay

The delay is defined as the total time for a packet to be transferred from the arrival node to the destination node. The time is measured in number of time slots. The average delay is obtained by sending packets in the network during a sufficiently long time period, and then calculating a mean value based on the delays for all packets sent.

6.2 Simulations

Tables 1-2 present the different simulations that are carried out. We have carried out simulations on 12 networks of 20 nodes. For each network, the simulations give a maximum throughput and a delay. Since the results from the networks can differ, an average throughput for all networks is calculated. The throughput is presented in Appendix B. We have carried out two different types of simulations. In the first, the links that are available for the combination with single isotropic antenna element for transmitting and receiving are also used for all beamforming combinations. To do this, the SNR threshold is increased by respective antenna gain. The results from these simulations are shown in section 7.1.1. This type of simulation is interesting to see how the capacity gain is effected when using the antenna array to suppress and decrease interferences. In the second type of simulation, the antenna array is used to suppress and decrease interferences, and increase the connectivity, i.e. generate an increased number of links. This implies that the antenna combinations will have different networks. These results are shown in section 7.1.2.

6.2.1 Capacity and average delay

The two tables below show the scenarios that are simulated to investigate how the use of an antenna array affects the capacity and average delay.

Varying the number of antenna elements

Table 1 shows the simulations carried out to investigate how the capacity gain and average delay in a network of 20 nodes are affected when the number of antenna elements is varied.

Table 1. Simulations in terrain Skara with 20 nodes.

	Combination 1	*Combination 2*	*Combination 3*	*Combination 4*
Antenna combination	Single antenna for transmitting and receiving.	Single antenna for transmitting. Adaptive beamforming for receiving.	Beam steering for transmitting and receiving.	Beam steering for transmitting. Adaptive beamforming for receiving.
Number of nodes	20	20	20	20
Number of antenna elements	1	6, 8	6, 8	6, 8
Terrain	Skara	Skara	Skara	Skara
Network	Stationary	Stationary	Stationary	Stationary

Varying the terrain

Table 2 shows the simulations carried out to investigate how the capacity and average delay in a network of 20 nodes, which have the same positions, are related to different terrains.

Table 2. Simulations in terrain Skara and Lomben with 20 nodes.

	Combination 1	*Combination 2*	*Combination 3*	*Combination 4*
Antenna combination	Single antenna for transmitting and receiving.	Single antenna for transmitting. Adaptive beamforming for receiving.	Beam steering for transmitting and receiving.	Beam steering for transmitting. Adaptive beamforming for receiving.
Number of Nodes	20	20	20	20
Number of antenna elements	1	8	8	8
Terrain	Lomben, Skara	Lomben, Skara	Lomben, Skara	Lomben, Skara
Network	Stationary	Stationary	Stationary	Stationary

Chapter 7

Results

This chapter presents the results from the different simulations.

As mentioned in Chapter 6, the simulations are carried out on 12 networks of 20 nodes, from which an average maximum throughput is calculated. To present the results, we have chosen a sample network. The sample network is chosen to have its maximum throughput near the average value from the first type of simulation. When making the choice of sample network, we considered only the networks from the first type of simulation. The frequency used is 300 MHz, the bit rate is 256 000 bits/second, and packets of equal size arrive to the network according to a Poisson process.

For absolute values of the results see Appendix B.

7.1 Capacity and average delay

The results for the different antenna combinations are presented in plots where the combinations have different colors.

- Black – combination 1, single isotropic antenna element for transmitting and receiving.
- Green – combination 2, single isotropic antenna element for transmitting and adaptive beamforming for receiving.
- Red – combination 3, beam steering for transmitting and adaptive beamforming for receiving.
- Blue – combination 4, beam steering for transmitting and receiving.

The x-axis of the plots represents the traffic arrival rate, which is measured in packets per time slot. The y-axis represents the average delay in the network, which is measured in time slots. For low traffic arrival rates there will be no packets queues. However, when the traffic arrival rate increases, queues arise. Finally, the delay reaches infinity due to the queues. This gives an asymptote, which represents the maximum throughput.

7.1.1 Increased SNR threshold

In these simulations, the same links that are available for single isotropic antenna elements are also used for antenna arrays. The results from these simulations are shown in Figures 8-10. Figure 8 shows the scenario with a network consisting of 20 nodes and 8 antenna elements in terrain Skara. The results from this scenario will be used as a comparison when studying the capacity gain and reduction in average delay when the number of antenna elements and the terrain are varied.

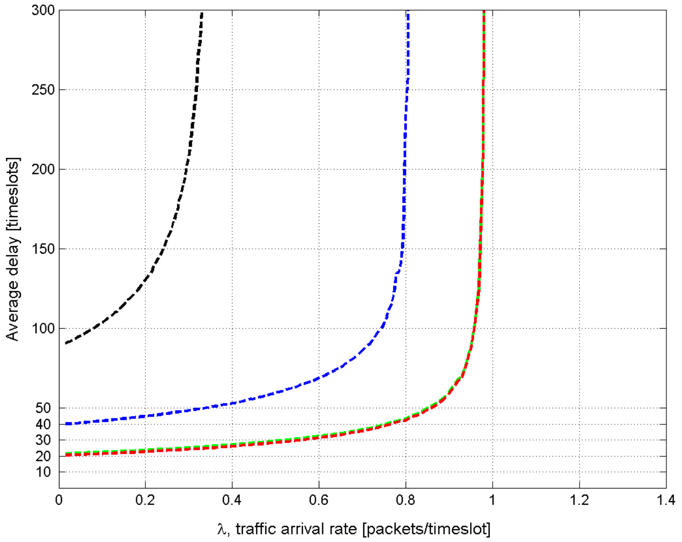


Figure 8. Average packet delay vs. traffic load for terrain Skara with 20 nodes and 8 antenna elements.

The results show that the capacity gain is large for all combinations where antenna arrays are used, and the average delays are low compared to combination 1 (single isotropic antenna element for transmitting and receiving), see Figure 8. Combination 3 (beam steering for transmitting and adaptive beamforming for receiving) and combination 2 (single isotropic antenna element for transmitting and adaptive beamforming for receiving) gives the highest capacity gains. The capacity gain for combinations 2 and 3 is about 180%, and for combination 4 about 130%. The results from the sample network concur relatively well with the average results in Appendix B.

In this study, one delimitation is that a node can only transmit or receive a single packet in a time slot. This implies that in a network of 20 nodes a maximum of 10 links can be used in the same time slot. This is why combinations 2 and 3 give the same results. By studying the STDMA schedule we can see that for combination 2 no more links can be added to a time slot, due to this delimitation.

The reason why combinations 2 and 3 give a higher capacity gain than combination 4 is that when using adaptive beamforming it is possible to steer the null directions. This means that more links can be allocated to the same time slot, i.e., the spatial reuse is increased. The result is a shorter STDMA schedule, which in this case where the same links are used, gives a higher capacity gain. An increased spatial reuse also results in a decreased average delay. When using beam steering for receiving, as in combination 4, the interferences are not suppressed as much as in adaptive beamforming. As a consequence the spatial reuse is not as high as when using adaptive beamforming, and thus the capacity gain is lower and the average delay is higher.

Varying the number of antenna elements

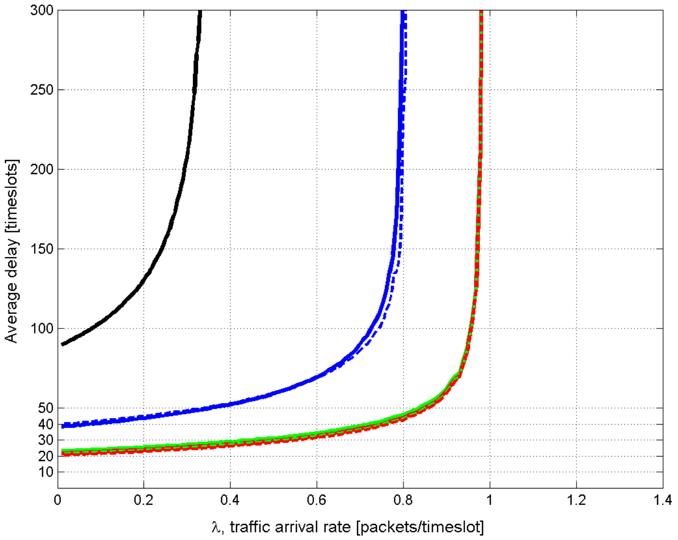


Figure 9. Average packet delay vs. traffic load for terrain Skara with 20 nodes. Comparison between 6 (solid) and 8 (dashed) antenna elements.

The results show no significant reduction in capacity gain when using 6 antenna elements instead of 8, see Figure 9. By studying the STDMA schedules for the different scenarios we can see that when using 6 antenna elements it is not possible to add additional links to the time slots. This is due to the delimitation that a node is only able to transmit or receive a single packet in a time slot. This implies that when using 8 antenna elements, the ability to suppress more interferences cannot be used. Thus, since the same network, with the same set of links, is used when using 6 antenna elements instead of 8, the results show no reduction in capacity. The average results in Appendix B show no significant improvement, which is line with the results from the sample network.

Varying the terrain

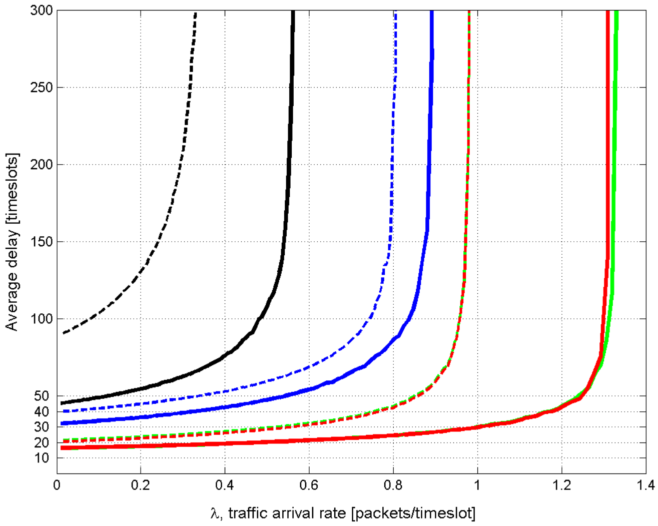


Figure 10. Average packet delay vs. traffic load with 20 nodes and 8 antenna elements. Comparison between different terrains; Lomben (solid) and Skara (dashed).

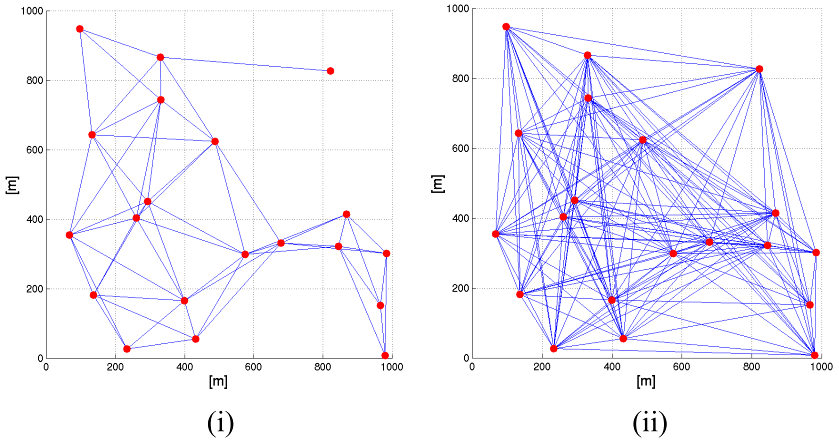
The results from the sample network show that the capacity is higher in Lomben than in Skara, see Figure 10. However, the capacity gain is lower in Lomben than in Skara. In Lomben combinations 2 and 3 show an improvement of about 135% in capacity. For combination 4 the improvement is about 60%. As mentioned earlier the capacity gain for combinations 2 and 3 in Skara is about 180%, and for combination 4 about 130%. The capacity gain is higher in Skara than in Lomben because interferences are fewer in Lomben, therefore the spatial reuse is higher when using single isotropic antenna elements.

When comparing the results from this sample network with the average results in Appendix B, we can see that maximum throughput for combinations 2 and 3 is higher than average. When studying the average results, the capacity gain is higher and the decrease in average delay is greater in Skara than in Lomben for all beamforming combinations, which agrees with the results from the sample network.

For combinations 2 and 3 in Skara the average results in Appendix B show an improvement of about 180% in capacity. For combination 4 the improvement is about 120%. In Lomben combinations 2 and 3 show an improvement of about 130% in capacity, whereas combination 4 improved by about 70%.

7.1.2 Increased connectivity

These simulations consider both the ability to suppress and decrease interferences, and the ability to increase connectivity when using antenna arrays. The results from these simulations are shown in Figure 12-14. The increased connectivity implies an increased number of links, see Figure 11.



(i) (ii)

Figure 11. Networks consisting of 20 nodes in Skara. In (i) single isotropic antenna elements are used for transmitting and receiving. In (ii) beam steering for transmitting and adaptive beamforming for receiving with 8 antenna elements are used. As shown in the figure, network (ii) has 356 links and network (i) has 134 links.

Figure 12 shows the scenario with a network consisting of 20 nodes and 8 antenna elements in Skara. This scenario will be used as a comparison when studying the capacity gain and average delay, when the number of antenna elements and terrain are varied.

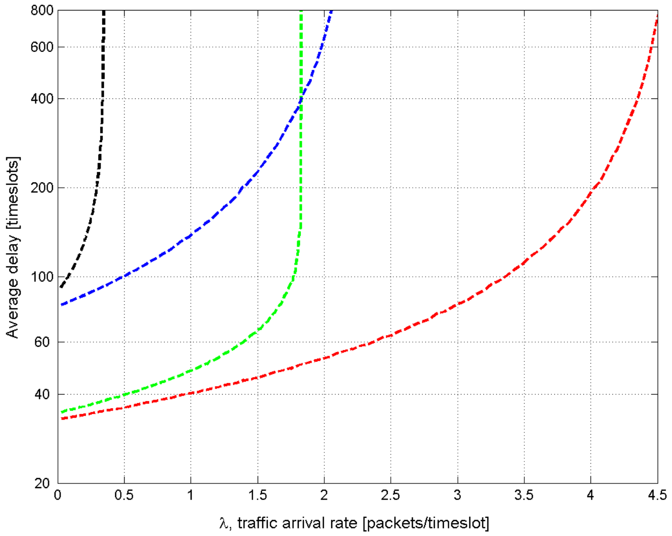


Figure 12. Average packet delay vs. traffic load for terrain Skara with 20 nodes and 8 antenna elements.

The results from the sample network show that combination 3 gives the highest capacity gain with about 1220%. Combination 4 is the second best, about 540%, and combination 2 has the lowest capacity gain, with about 425%. When studying the average results we can see that the maximum throughput for combination 3 in the sample network is higher than average. The average capacity gain for combination 3 is about 855%. We can also see that the maximum throughput for combination 2 is higher than for combination 4, which is not the case for the sample network. When studying the maximum throughput for the 12 networks separately, we found that this is also the case for another two networks. For combination 2 the average capacity gain is 450%, and 385% for combination 4.

Combination 3 gives a higher capacity gain than combination 2 partly because of the spatial reuse, and partly because of the increased number of links.

The capacity gain for combination 3 is higher than for combination 4 because in combination 3 adaptive beamforming is used for receiving. With adaptive beamforming it is possible to suppress more interferences. Thus, the spatial reuse is increased, and the STDMA schedule is shortened.

The results also show that the average delays are lower for combinations 2 and 3 compared with combinations 1 and 4. Combinations 2 and 3 have a lower average delay compared with combination 4, as the spatial reuse is higher.

Varying the number of antenna elements

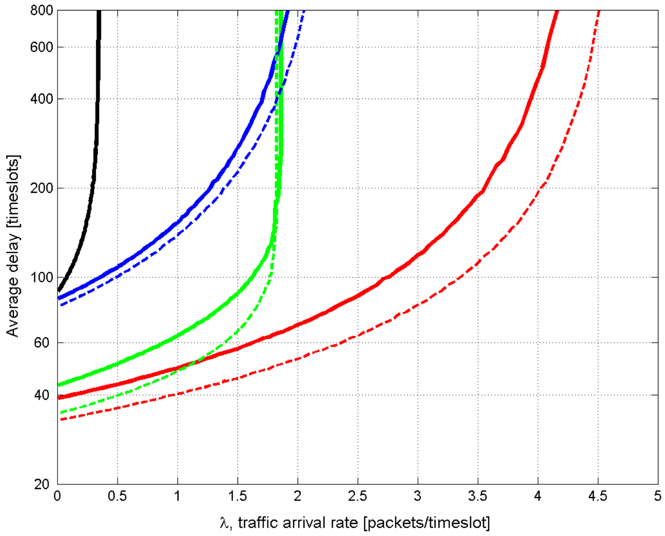


Figure 13. Average packet delay vs. traffic load for terrain Skara with 20 nodes. Comparison between 6 (solid) and 8 (dashed) antenna elements.

For combination 2 the decrease in capacity gain is not significant when using 6 antenna elements instead of 8, see Figure 13. However, when studying the average results, we can see that the capacity gain is about 390% when using 6 antenna elements, and about 450% when using 8 antenna elements. This is because more antenna elements increase the ability to suppress interferences. An explanation of the results from the sample network could be that even though the number of antenna elements is increased, it is not enough to suppress the additional interferences. This implies that more time slots must be used, and the capacity gain is not increased.

The results from the sample network for combination 3 shows a capacity gain of about 1160% when using 6 antenna elements, and 1220% when using 8 antenna elements. The scenario with 8 antenna elements has a few more links than the scenario with 6 antenna elements. By studying the STDMA schedules for these scenarios we can see that the number of time slots in the schedule for 8 antenna elements is less than for 6 antenna elements. As mentioned before, this implies that by using 8 antenna elements more interferences can be suppressed, and therefore more links can be used in the same time slot, i.e. the spatial reuse of the time slots is improved. The high spatial reuse gives a shorter STDMA schedule, and with that the capacity gain will increase. The average results agree with the results from the sample network. However, for the sample network the capacity gains are somewhat above average.

Combination 4 has a capacity gain of about 500% when using 6 antenna elements, and 540% when using 8 antenna elements. As in the case of combination 3, the capacity gain is due to the high spatial reuse. This result agrees with the average results.

All beamforming combinations have a higher average delay when using 6 antenna elements instead of 8 because the spatial reuse is lower.

Varying the terrain

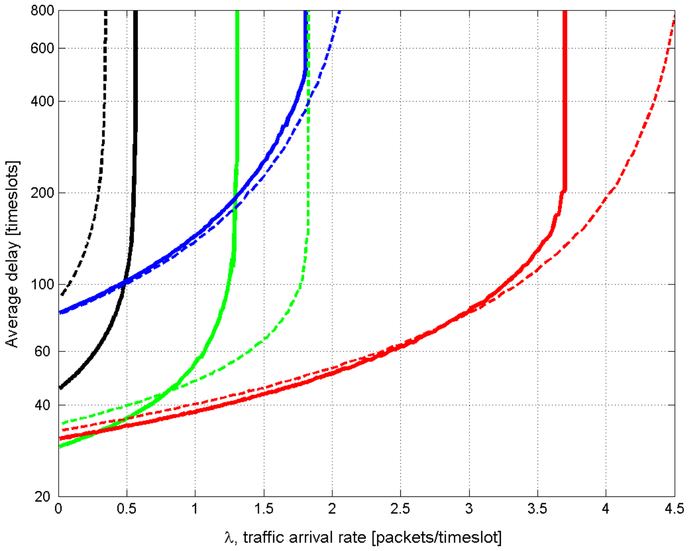


Figure 14. Average packet delay vs. traffic load with 20 nodes and 8 antenna elements. Comparison between different terrains; Lomben (solid) and Skara (dashed).

The results show higher capacity gains in Skara than in Lomben for all beamforming combinations, see Figure 14. As mentioned in section 7.1.1, the explanation is that the spatial reuse is already higher for combination 1 in Lomben than in Skara, since the interferences are fewer. This implies that the benefits of using antenna arrays in Skara are higher than in Lomben. The results from the sample network are verified by the average results. However, we can see that the capacity gains for the sample network are slightly above average.

Combination 2 has a lower average delay in Lomben than in Skara, which could be due to the spatial reuse being higher or the number of links being fewer. Combination 3 has a lower average delay in Lomben than in Skara probably because the number of links is fewer. The average delays for combination 4 are similar in both terrains.

Chapter 8

Conclusions

We have investigated how capacity and average delay can be improved in an Ad Hoc network with STDMA by using antenna arrays. The study is based on different antenna combinations consisting of single isotropic antenna elements, beam steering and adaptive beamforming. The beam steering algorithm used is conventional beamforming, and the adaptive beamforming algorithm used is reference-based-signal beamforming.

We have also studied how the number of antenna elements, the terrain, and an increased connectivity due to the antenna arrays affect the performance measurements.

We found that capacity is improved by up to 1200% and that the average delays are decreased when using antenna arrays instead of single isotropic antenna elements. Depending on the beamforming combination used, the capacity gain and average delay reduction will differ. The highest capacity gain is always achieved when using beam steering for transmitting and adaptive beamforming for receiving. We also found that the way of using the antenna array will affect the capacity gain and average delay. The capacity gain is higher when the antenna array is used not only to suppress and decrease interferences, but also to increase the connectivity.

The capacity gain is also higher when using more antenna elements for a network with a high number of links, than with fewer. However, this capacity gain is relatively small compared to the capacity gain achieved when using antenna arrays instead of single isotropic antenna elements. When the connectivity is high, the average delay is decreased when using an increased number of antenna elements, since the ability to suppress interferences is higher.

We also found that the benefit of using antenna arrays compared with single isotropic antenna elements is high both in rough and flat terrain. However, the benefit from antenna arrays is higher in flat terrain than in rough. The reason is that the interferences are less in a rough terrain, and thereby the spatial reuse is higher when using single isotropic antenna elements. Thus, the capacity gain and the average delay reduction are higher in flat terrain.

Chapter 9

Future work

This chapter suggests a number of topics for future work within this area.

9.1.1 Jamming

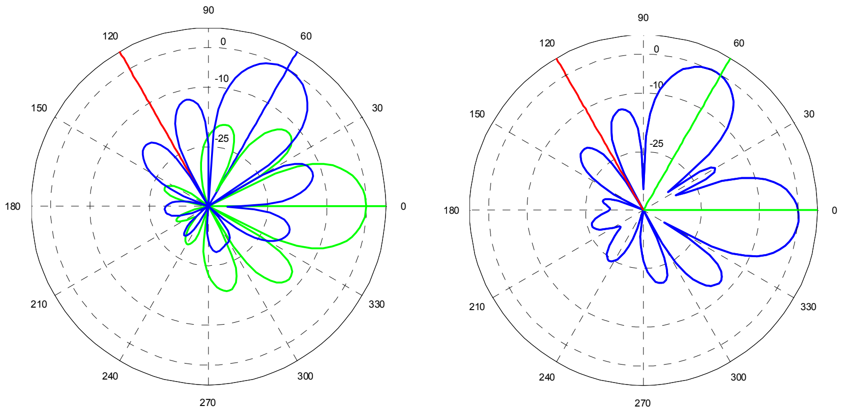
In a military communication system, jamming is a serious threat. Jammers can affect the Ad Hoc network in two ways. Firstly, one or several nodes can be totally disconnected from the network. Secondly, one or several links may not be functional since the SINR becomes too low. This results in decreased capacity and increased average delays in the network. To be able to maintain communications in the military network it is therefore important to have the ability to suppress these jammers. Antenna arrays make this possible by minimising the sensitivity in the direction of the jammer. Therefore it would be interesting to study a scenario where a jammer is present.

9.1.2 Adaptive beamforming for transmitting

Adaptive beamforming for transmitting is hard to implement, since it requires information that is not always available, e.g. how the channel changes over time. Despite this, it is interesting to investigate the approach of adaptive beamforming for transmitting to see how much the gain will increase when assuming full knowledge about the channel, node positions, etc. When using adaptive beamforming for transmitting, the output power can be directed towards a desired receiver, and the output power can be minimised in the direction of other nodes. Thereby the interferences to other users can be minimised.

9.1.3 Multiple beamformer

This study is based on the assumption that a node can only transmit or receive one packet successfully in a time slot. One interesting aspect is therefore to investigate the ability to transmit or receive multiple packets simultaneously in different lobes. This is achieved by using either multiple parallel beamformers or only one beamformer, which can create more than one major lobe, see Figure 15. A disadvantage of using multiple parallel beamformers when transmitting is that the side lobes from one beamformer may interfere with the major lobe of the other beamformer. A disadvantage of using only a single beamformer is that the ability to suppress interferences when receiving and steer null directions when transmitting decreases.



(i) (ii)

Figure 15. (i) shows multiple parallel beamformers and (ii) shows a single beamformer with two major lobes.

9.1.4 Mobility

Antenna arrays enable adaption to changes in the scenario, which means that the main lobe of a beam steered antenna array can always be in the direction of the desired receiver/transmitter. Moreover, the effect of interferences from other directions will be reduced. This entails that the SINR will improve. A higher SINR will contribute to a longer existence of the links, i.e. an increased survival time of the STDMA schedule. Therefore the links can exist longer in mobile scenarios. When using an adaptive antenna, it is possible to continuously change the array pattern such that interferences are suppressed. Hence, if the interference level from any node increases due to the mobility, a node equipped with an adaptive antenna can compensate for this and suppress the interferences effectively.

Furthermore, it would be of great interest to consider the multipath effect, more realistic channel models and beamforming behaviour with imperfections.

9.1.5 Power control

When using power control, the antenna power is adjusted to the optimal level for each link. This implies that the interferences will be lower compared to a network with no effect control. The power control would therefore have a greater importance when considering a network consisting of a high number of nodes, since the interferences increases with the number of nodes. Thus, a further study could investigate how much the capacity gain increases when using power control in the network.

References

[1] S. Basagni, “A mobility–transparent deterministic broadcast mechanism for Ad hoc networks,” *IEEE Transaction on Networking*, vol. 7, no. 6, pp. 799-807, December 1999.

[2] A. Iwata, C. Chiang, G. Pei, M. Gerla and T. Chen, “Scalable routing strategies for Ad hoc wireless networks,” *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1369-1379, August 1999.

[3] M. Sánchez and J. Zander, “Adaptive antennas in spatial TDMA multihop packet radio networks,” RadioVetenskap och Kommunikation 99, Karlskrona, Sweden, 1999.

[4] J. Grönkvist, “Spatiell tidsmultiplex – algoritmer och utvärdering,” (RR[4]) FOA-R- -98-00781-504-- SE, Defence Research Establishment, Division of Command and Control Warfare Technolgy, Sweden, June 1998.

[5] J. Grönkvist, E. Englund, A. Hansson and C. Jönsson, “Spatial TDMA for multi-hop radio networks,” (RR) FOA-R- - 99-01223-504- - SE, Defence Research Establishment, Division of Command and Control Warfare Technology, Sweden, September 1999.

---

[4] Research Report

[6] J. Frisell and A. Sennerbrant, “Konflikthantering i flerhoppsnät”, (RR) FOA-R- -00-01453-504- - SE, Defence Research Establishment, Division of Command and Control Warfare Technology, Sweden, 2000.

[7] B. Buckley and B. Van Veen, ”Beamforming: A verstile approach to spatial filtering,” *IEEE ASSP Magazine*, vol. 5, no. 2, pp. 4-24, April 1988.

[8] L. C. Godara, “Application of antenna arrays to mobile communications, Part II: Beam-forming and direction-of-arrival considerations,” *Proceedings of the IEEE*, vol. 85, no. 8, pp. 1195-1245, August 1997.

[9] M. Sánchez, T. Giles and J. Zander, “CSMA/CA with beam forming antennas in multi-hop packet radio,” Radio Communication System Laboratory, Department of Signals, Sensors and Systems, Royal Institute of Technology, Stockholm, Sweden, 2000.

[10] J. Grönkvist, “Traffic controlled spatial reuse TDMA in multi-hop radio networks,” in *PIMRC ’98, IEEE Personal, Indoor and Mobile Communications,* vol. 3, pp. 1203-1207, 1998.

[11] A. Ephremides and T. Truong, “Scheduling broadcast in multihop radio networks,” *IEEE Transactions on Communications*, vol. 38, no. 4, pp. 456-460, April 1990.

[12] C. Hammar, “Trådlösa lokala nätverk –en utvärdering av prestanda”, HS-IDA-EA-98-111, Institutionen för datavetenskap, Högskolan i Skövde, Sweden, 1998.

[13] L. Kleinrock and R. Nelson, ”Spatial-TDMA: A collision-free multihop channel access protocol,” *IEEE Transactions on Communications*, vol. COM-33, pp. 934-944, September 1985.

[14] C. A. Balanis, *Antenna theory analysis and design*, ISBN-0-471-60352-X, John Wiley & Sons, Inc., USA, 1983.

[15] J. Grönkvist, E. Englund and A. Hansson, “Throughput in Static Allocation Multihop Radio Networks,” Department of Communication Systems, Defence Research Establishment, (RR) FOA Memo 00-3192/L, Linköping, Sweden, June 2000.

[16] J. C. Liberti and JR. T. S. Rappaport, *Smart antennas for wireless communications: IS-95 and third generation CDMA applications*, ISBN 0-13-719287-8, Prentice Hall Inc., New Jersey, 1999.

[17] J. Litva and T. Kwok-Yeung, *Digital beamforming in wireless network*, ISBN-0-89006-712-0, Artech House Inc., Norwood, 1996.

[18] R. T. Compton Jr, *Adaptive Antennas: Concepts and Applications*, Prentice Hall, 1988.

[19] B. Widrow, P. E. Mantey, L. J. Griffiths and B. B. Goode, “Adaptive antenna systems,” *Proceedings of the IEEE*, vol. 55, pp. 2143-2159, December 1967.

[20] B. Asp, G. Eriksson and P. Holm, ”Detvag-90 –final report,” (RR) FOA-R—97-00566-504- -SE, Defence Research Establishment, Linköping, Sweden.

[21] R. Ramanathan, “On the performance of Ad hoc networks with beamforming antennas,” *Proceedings of MobHoc 2001*, pp. 95-105, October 4-5 2001.

[22] J. Ward and R. Compton, “High throughput slotted ALOHA packet radio networks with adaptive arrays,” *IEEE Transactions on communications, v*ol. 41, no. 3, pp. 460-470, March 1993.

[23] R. T Compton Jr. and F. W Vook, “Bandwidth performance of linear adaptive arrays with tapped delay-line processing,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 28, no. 3, pp. 901-908, July 1992.

[24] H. Krim and M. Viberg, “Two decades of array signal processing research,” *IEEE Signal Processing*, vol. 13, no. 4, pp. 67-94, July 1996.

[25] M. Agrawal and S. Prasad, “Robust adaptive beamforming for wide-band, moving, and coherent jammers via uniform linear arrays,” *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 8, pp. 1267-1275, August 1999.

[26] O. L. Frost III, “An algorithm for linearly constrained adaptive array processing,” *Proceedings of the IEEE*, vol. 60, pp. 926-935, August 1972.

[27] D. A. Maltz, J. Broch and D. B. Johnson, “Lessons from full-scale multihop wireless Ad hoc network testbed,” *IEEE Personal Communications*, vol. 8, pp. 8-15, February 2001.

[28] S. Desilva and R. D. Samir, “Experimental evaluation of a wireless Ad hoc network, ” in *Proceedings of the 9th International Conference on Computer Communications and Networks,* October 2000.

[29] E. Royer and C-K Toh, “A review of current routing protocols for ad-hoc mobile wireless networks,” *IEEE Personal Communications Magazine*, vol. 6, pp. 46-55, April 1999.

[30] L.M Feeney, B. Ahlgren and A. Westergren, “Spontaneous Networking: An Application-Oriented Approach to Ad Hoc Networking,” *IEEE Communications Magazine*, vol. 39, no. 6, pp. 176-181, June 2001.

[31] D. Bertsekas and R. Gallager, *Data Networks -second edition*, ISBN-0-13-200916-1, Prentice Hall, USA, 1992

Appendix A

This appendix explains the terminology used throughout this report.

Baseband signal
Before sampling, the signal it is often down-converted to baseband, which means that the carrier frequency is dropped and the information frequency is obtained.

Broadband signal
The term broadband has many definitions, for example that the capacity must exceed 2 Mbit/second. In this study the term broadband signal means that the amplitude and phase of the signal vary across the antenna array, and that the signal covers a wide frequency range.

Connectivity
The connectivity is defined as the percentage share of nodes in the network that a node has a direct link to.

Delay
The time elapsed from the packet being sent by a source until the packet reaches its destination.

Link
A pair of nodes (v_i, v_l) can establish a link if the SNR between the nodes exceeds a certain threshold. A link (i, j) exists if a message can be transmitted directly from node v_i to node v_j, see Figure 16.

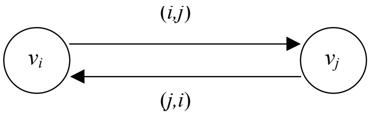


Figure 16. Link (i, j) and link (j, i).

Narrowband signal

In this study a narrowband signal means that the amplitude and phase of the signal vary slowly across the antenna array, and that the signal does not cover a wide frequency range.

Node

A node represents a radio station in the radio communication network. The nodes are placed in a coordinate system where each node has its own coordinates. Every node has a given transmitted power and an antenna gain. All nodes can transmit or receive packets. For each link only one packet can be sent in each time slot and a node is only able to transmit/receive a packet to/from one node at a time. In the network the nodes are defined and numbered as v_i, where i = 1...N.

Packets

Packets are small pieces of data that are transferred across a network. A packet contains a header, for example routing information, and data, see Figure 17.

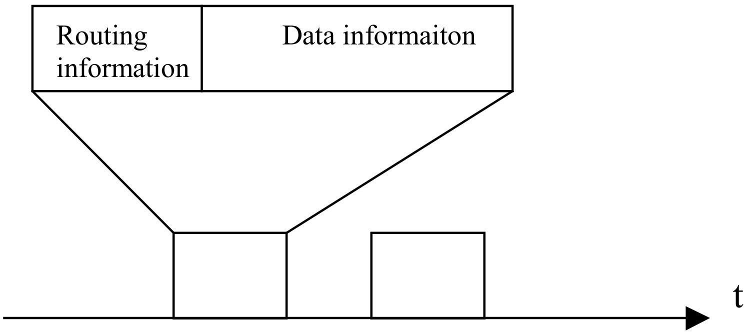


Figure 17. Packets.

Plane wave

In this study we assume plane waves, which means that the field components are essentially transverse and the angular distribution is independent of the radial distance for which the measurements are made. This assumption can be made in the far-field region, whose inner boundary is the radial distance $R = 2D^2 / \lambda$ and the outer one at infinity. The far-field region is “that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the antenna” [14].

SINR

The Signal-to-Interference-plus-Noise Ratio (SINR) relates the received signal power to the power of the sum of the interference signals plus the power of the system noise. The SINR determines whether a link in a network can be used or not. SINR can be calculated as

$$SINR(v_i, v_j) = \frac{\dfrac{P_t(v_i) \cdot G_t(v_i, v_j) \cdot G_r(v_i, v_j)}{L_b(v_i, v_j)}}{F(v_j) \cdot k \cdot T_0 \cdot R + \sum_{l \in L} \dfrac{P_t(v_l) \cdot G_t(v_l, v_j) \cdot G_r(v_l, v_j)}{L_b(v_l, v_j)}} \qquad \text{(A.1)}$$

where

$P_t(v_i)$	transmitted power of node v_i;
$G_t(v_i, v_j)$	antenna gain for the transmitting node v_i in the direction of the receiving node v_j;
$G_r(v_i, v_j)$	antenna gain for the receiving node v_j in the direction of the transmitting node v_i;
$L_b(v_i, v_j)$	basic path-loss between the transmitting node v_i and the receiving node v_j;
$F(v_j)$	noise factor, defined as the ratio between the temperature of the noise source and the reference thermal noise source with temperature $T_0 = 290\ K$.;
k	Boltzmann’s constant, $k = 1{,}38 \cdot 10^{-23}\ J / K$;
R	bit rate;

L	the set of all nodes v_l which send at the same time as node v_i, $l \neq i$.

SNR

Signal-to-Noise Ratio (SNR) relates the received signal power to the power of the system noise. The SNR decides the quality of a radio communication link. SNR can be calculated as

$$SNR(v_i, v_j) = \frac{P_t(v_i) \cdot G_t(v_i, v_j) \cdot G_r(v_i, v_j)}{L_b(v_i, v_j) \cdot F(v_j) \cdot k \cdot T_0 \cdot R} \tag{A.2}$$

The terms in (A.2) are defined in the same way as in (A.1).

Survival time of the STDMA schedule

The survival time of the STDMA schedule is the time period for which the schedule is usable in the network. In this study it is defined as the time elapsed until one link no longer exists since the SINR is below a certain threshold.

Maximum throughput

The maximum throughput gives a value of how many packets per time slot that can be transmitted without resulting in an infinite delay.

Time slot

A time slot is defined as the time available for a node to transmit one packet to another node within one hop.

Weight

The weight is a coefficient that can be used to modify the phase and/or the amplitude of the signal in each antenna element.

Appendix B

Combination 1 Single isotropic antenna element for transmitting and receiving.

Combination 2 Single isotropic antenna element for transmitting and adaptive beamforming for receiving.

Combination 3 Beam steering for transmitting and adaptive beamforming for receiving.

Combination 4 Beam steering for transmitting and receiving.

Increased SNR	**Maximum throughput**	**Variance of the maximum throughput**
Skara, 20 nodes, 6 antenna elements	0.39	0.01
Skara, 20 nodes, 6 antenna elements	1.11	0.17
Skara, 20 nodes, 6 antenna elements	1.12	0.16
Skara, 20 nodes, 6 antenna elements	0.82	0.07
Skara, 20 nodes, 8 antenna elements	0.39	0.02
Skara, 20 nodes, 8 antenna elements	1.12	0.16
Skara, 20 nodes, 8 antenna elements	1.13	0.10
Skara, 20 nodes, 8 antenna elements	0.86	0.06

Lomben, 20 nodes, 6 antenna elements	0.53	0.00
Lomben, 20 nodes, 6 antenna elements	1.21	0.06
Lomben, 20 nodes, 6 antenna elements	1.21	0.06
Lomben, 20 nodes, 6 antenna elements	0.88	0.01
Lomben, 20 nodes, 8 antenna elements	0.53	0.00
Lomben, 20 nodes, 8 antenna elements	1.20	0.06
Lomben, 20 nodes, 8 antenna elements	1.21	0.06
Lomben, 20 nodes, 8 antenna elements	0.90	0.00

Increased connectivity	**Maximum throughput**	**Variance of the maximum throughput**
Skara, 20 nodes, 6 antenna elements	0.39	0.02
Skara, 20 nodes, 6 antenna elements	1.90	0.26
Skara, 20 nodes, 6 antenna elements	3.53	0.83
Skara, 20 nodes, 6 antenna elements	1.79	0.11
Skara, 20 nodes, 8 antenna elements	0.40	0.02
Skara, 20 nodes, 8 antenna elements	2.19	0.59
Skara, 20 nodes, 8 antenna elements	3.82	1.28
Skara, 20 nodes, 8 antenna elements	1.94	0.10

Lomben, 20 nodes, 6 antenna elements	0.53	0.00
Lomben, 20 nodes, 6 antenna elements	1.67	0.08
Lomben, 20 nodes, 6 antenna elements	2.51	0.44
Lomben, 20 nodes, 6 antenna elements	1.39	0.06
Lomben, 20 nodes, 8 antenna elements	0.53	0.00
Lomben, 20 nodes, 8 antenna elements	1.70	0.08
Lomben, 20 nodes, 8 antenna elements	3.07	2.04
Lomben, 20 nodes, 8 antenna elements	1.61	0.15